Chapter 5

Geodynamic and Tectonostratigrafic Study of a Continental Rift: The Triassic Cuyana Basin, Argentina

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Additional information is available at the end of the chapter

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1. Introduction

The stress and strain resultant from geodynamic processes control the uplifting and subsidence of different portions of the crust so sedimentary basins can be considered pieces of the earth which have suffered prolonged subsidence related to thermo-mechanical processes. According to these latter, a mechanical analysis of subsidence in any basin can be used for interpreting the regional distribution of depositional sequences; similarly the origin of the sedimentary sequences can be related back to the tectonic activity which controlled the insertion and evolution of the sedimentary basin [1]. Depositional sequences result from a complex interaction of the supply of sediments, the availability of the accommodation space (both with tectonic components), sea level variations (which also may have a significant tectonic influence) and climate variations. The first-order control on basin geometry is the deformation field resulted from the tectonic activity and is a fundamental control on sedimentation and the location of their resulting environments. For each basin, the geometry of the main faults or the lithospheric flexure should provide the final morphology of the trough and the resulting subsidence and thus, will control the sedimentation rate, grain size, channel migration, avulsion episodes and the development of flood plains and/or lakes.

The Cuyana Basin corresponds to a passive continental rift, *sensu* [2] developed during Triassic times as a consequence of the early Mesozoic breakup of Gondwana (Permian to Late Triassic-Early Jurassic) e.g. [3, 4]. It was located in its western southernmost portion over a wide belt of older accreted Eopaleozoic terranes, known as Gondwanides orogen. This latter was an extensive belt composed of contemporaneous orogens of Palaeozoic age and their related basins located along the southern Gondwana margin, it was firstly defined by Keidel [5] but du Toit [6] referred to as "Samfrau geosyncline". The Cuyana Basin is composed of several asymmetric half-grabens linked by accommodation zones that were partially or completely disconnected in the early rifting phase [7, 8]. This geometry and the coeval tectonic activity that was mostly characterized by recurrent extensional pulses are thought to be one of the major factors in the evolution of the sedimentary sequences and the complex environmental relationships that this basin exhibits. Its continental deposits can be considered as a whole a second-order depositional sequence divided into three third order-sequences related with regional to local processes [9].

Much of the research on this basin has been conducted in the Cacheuta depocenter where an intense hydrocarbon exploration and production has been held in the past decades [10 to 13]. Instead, the northernmost sections of the Cuyana Cuyana Basin, located in the San Juan province, have been studied in detail by [9, 14-21].

Interbasinal correlations along the whole basin were due to [7, 18, 22 to 24] who considered the separate half-grabens of San Juan and Mendoza provinces as a single trough. Age control in the basin traditionally has been based on biostratigraphy e.g. [20, 25 to 30]. The studied area is part of a fold and thrust belt where complex structures and diverse inversion tectonics phenomena gave place to inverted subbasins composed of normal faults with reactivated inverse displacement, new inverse faults, and fault propagation folds [8, 31]. Consequently, lithostratigraphy and biostratigraphy proved to be insufficient to understand sequences contrast along the basin, see [32] for discussion. By the 1990s modern stratigraphic tools have also been applied in an attempt to establish a more precise correlation among depocenters and even between the active and flexural margin of the Rincón Blanco trough, which are presently disconnected [8, 9, 20] but much uncertainty remained because of the lack of absolute age data in the basin as a whole. Presently, a more complete chronostratigraphic control has been achieved using the proposed cyclostratigraphy scheme of [13] with isotopic dating [29, 32 to 34] which permitted to arrive to an enhanced evolutionary model.

Classically, the Cuyana Basin has been considered as a passive rift developed as a consequence of extensional to transtensional forces resulted of the collapse of a Permian orogen and the beginning of the Gondwana breakup, the stratigraphic features represent the interplay between tectonics (subsidence-uplift) and sediment accumulation rates. The evolution of the Gondwanides along the southern portion of Gondwana was a key process through which the Triassic basins of Argentina developed. In this dominant geodynamic framework it is emphasized here that making correlations can highlight similarities and differences among basins and even within a given one, as it is the case of the Cuyana Basin. Subsidence analysis of the subsurface Bermejo and outcropping Ischigulasto-Villa Unión-Marayes and Cuyana basins (Figure 1) reveals the existence of notably various episodes of accelerated subsidence during Middle to Late Triassic, suggesting that all of them share a common tectonic history.

It is explored here these results in detail integrating geodynamic and tectonostratigraphic concepts to understand the rift evolution and the history of its infilling. The resulting data, permitted to understand the coeval deformation and the tectonic processes acting on the lithosphere in the western margin of Gondwana.

2. Geological setting of the Cuyana Basin

Related to the Gondwanan Orogeny, that affected the western margin of southern South America (Permian to the Late Triassic-Early Jurassic) and the beginning of the Mesozoic Gondwana breakup, a series of rifts were developed (Figure 1). They correspond to a complex system of rapidly subsiding, NNW-SSE trending narrow asymmetric half-grabens bounded by predominantly normal faults in one margin that parallels the grain of older Paleozoic structures e.g. [9, 12, 19, 36 to 38]. The border fault is sometimes segmented with segment boundaries marked by change in strike or fault overlap, relay ramps, transfer faults and rider blocks(Figure 2). The notable increase in thickness towards the center border fault suggests that the structures were syndepositionally active and thus it is proposed here the architecture and fill were influenced by the geometry and the displacement of the bounding normal faults.

Among them, the Cuyana Cuyana Basin is the largest Triassic rift basin of western Argentina and considered to extend over an area of more than 60.000 Km^2. It corresponds to a passive continental rift developed during differential intraplate stresses derived from a backarc extension acting on a normal crust and moderate thermal flux [9]. At present, it underlies a lowland segment of the Argentine foreland but several exposures are along both flanks of the Precordillera, in Mendoza and San Juan provinces (Figure 1). The rift is composed of several asymmetric half-grabens roughly triangular in cross section, and linked by accommodation zones [7, 8] which correspond to Cacheuta, Las Peñas-Santa Clara, Rincón Blanco, Puntudo General Alvear, Ñacuñan and Beazley (see Figure 1). Border faults (BF) of the Cuyana Basin strike obliquely to the maximum extension direction (NNE-SSW), have a stepping geometry and opposite dip directions (Cacheuta and Santa Clara-Rincón Blanco) causing the faulted and hinged margins sometimes shift from side to side of the rift basin as it is evident between Cacheuta and Santa Clara subbasins e.g. [7, 9, 11], or keep the same dip orientation as between Santa Clara, Rincón Blanco and Puntudo depocenters (Figure 2). Each segment of these master structures shows tips that are marked by a change in strike or fault overlap, relay ramps and rider blocks. Most of them were controlled by the normal to oblique reactivation of pre-existing zones of weaknesses in the crystalline basement, and thus main border fault exhibits N-S and NNW-SSE direction while accommodation and transfer zones between main Puntudo, Rincón Blanco and Cacheuta depocenters display a mostly NNE-SSW direction. Major segments do not become hard linked and the displacement was partitioned among several segments without being physically connected. In this way, intrabasinal highs could persist throughout synrift and postrift sedimentation along the whole basin. The lack of polarity reversals in the northern segment is attributed to the basement fabric control with fault reactivation of ancient N-S and NNW-SSW structures. In particular, within Rincón Blanco depocenter, the border fault is segmented and its closer spacing segments hard-linked with evident transfer of displacement from the southern to northern segments (Figure 2) [1, 8]. The restricted half-grabens were separated by left-oblique-slip (left lateral?), WNW (Az 112°) that are oblique to the border fault.

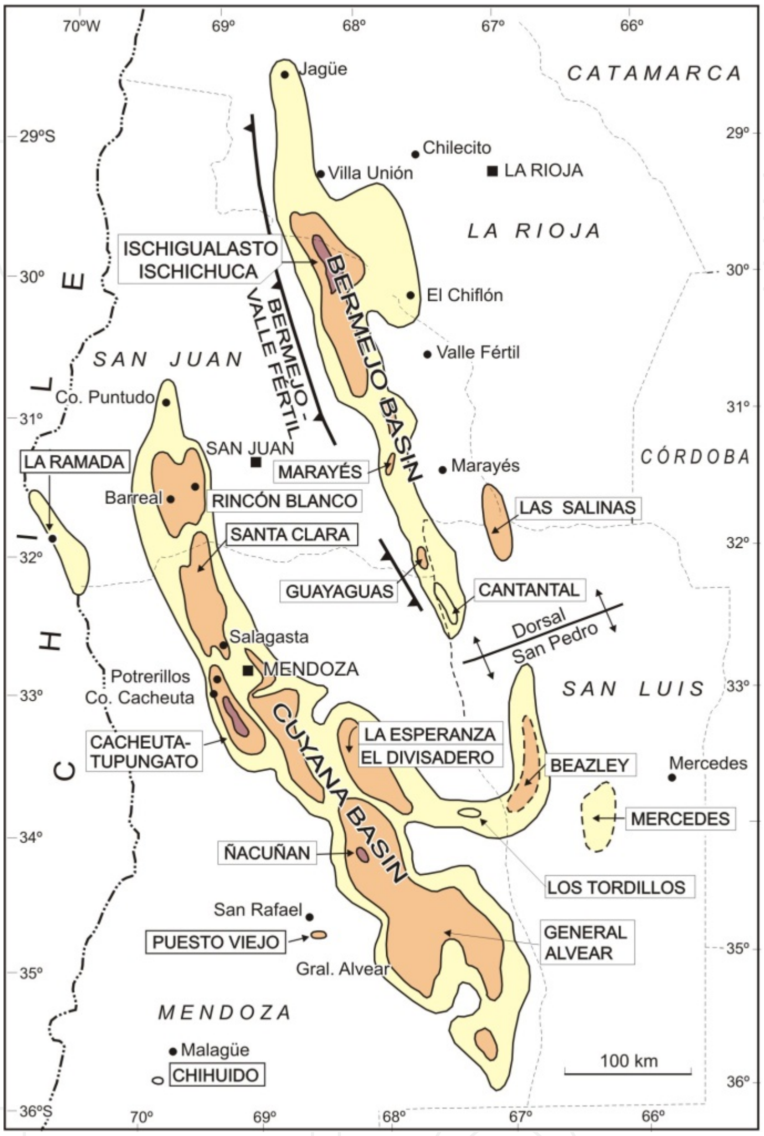

Figure 1. Triassic rift basins of central-western Argentina and the main subbasins. From [35].

The Cuyana Basin contains, approximately, up to 3700 meters of continental rocks of predominantly alluvial, fluvial, and lacustrine origin interbedded with tuffs of coeval volcanism with intraplate affinities e.g. [11, 39]. The notable increase in thickness towards the border faults suggests that these structures were syndepositionally active. Field studies and seismostratigraphic analysis show that changes in sequence geometry occurred in-phase with intra-continental elastic stress relaxation, as fault reactivation and probable basement reworking, during the quasistatic event on the western margin of Gondwana. These recurrent extensional pulses that controlled the extension along the Cuyana Basin impinged several different characteristic to the infilling of the Cerro Puntudo, Rincón Blanco and Cacheuta depocenters and thus they will be treated in separate items.

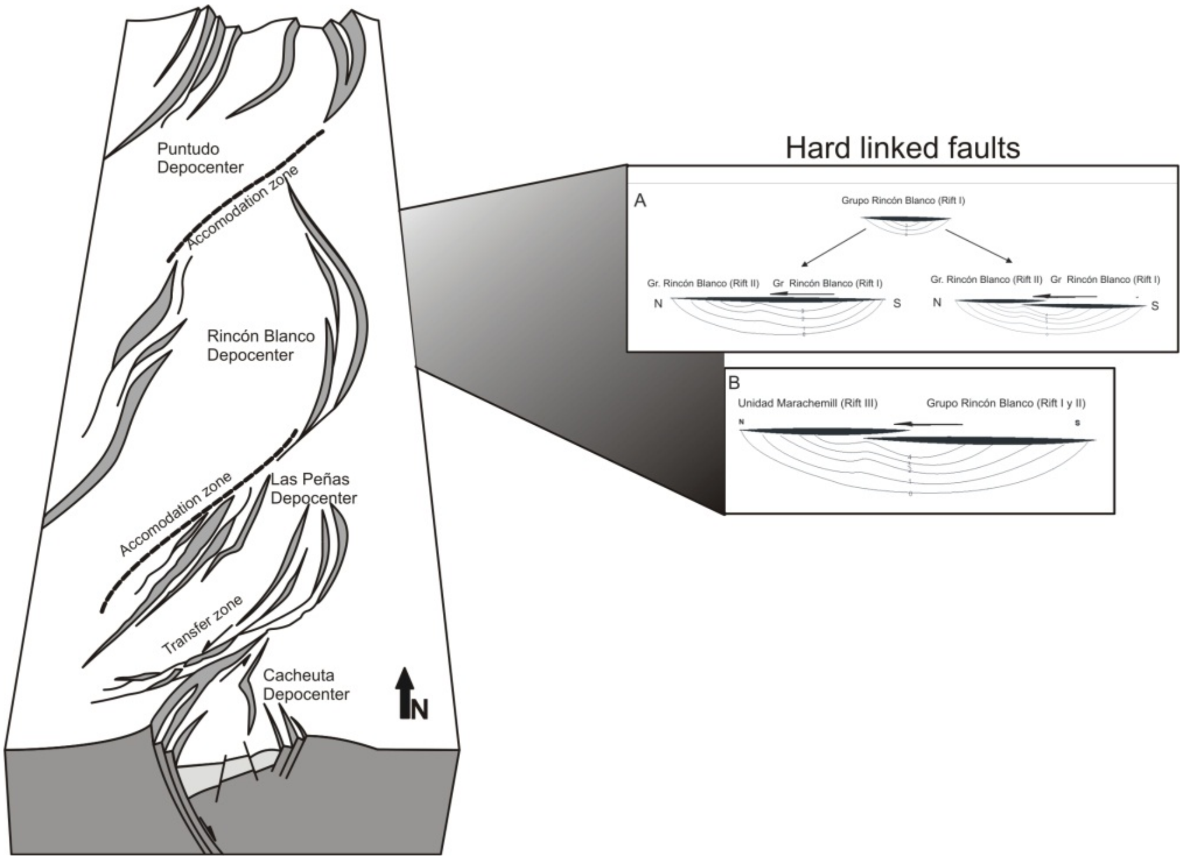

Figure 2. Cuyana Basin main depocenters. Border faults (BF) have a stepping geometry and opposite dip directions (Cacheuta and Santa Clara-Rincón Blanco) or keep the same dip orientation as between Santa Clara, Rincón Blanco and Puntudo depocenters. Major segments are related through accommodations zones which constitute intrabasinal highs. To the right, the scheme shows a plan view of the Rincón Blanco trough whose segments became hard linked. From Barredo & Ramos [1].

Extension took place along three phases, named Rift I, II and III and their corresponding synrift deposits by Barredo [9]. During Synrift I, the deposits were restricted to a series of partially isolated depressions. Thus, in proximal positions the alluvial coarse clastic facies are covered and interfingered with medium to fine-grained sandstones and tuffs interpreted as deposited in fluvial, and lacustrine/playa-lake settings e.g. [8, 9, 13, 20, 23, 26]. This first sequence is separated by a regional unconformity by the second depositional phase or Synrift II. It is a fining-upward sequence which consists, in general, of cross-bedded sandstones, black shales and tuffs, all related to braided to high sinuosity-river systems which grade into a widespread lacustrine setting. Finally, this second rifting stage passes upward to shallow lacustrine to fluvial sandstones, shales, and tuffs deposited during the early to late post-rift. This shallowing-upward succession is widespread in the basin and displays an onlap relationship with the underlying beds, directly overlying Paleozoic basement [8, 9, 13]. During this stage, there was a renewal of the subsidence in the basin. Recent investigations permitted to identify a the third extensional event during early Late Triassic (to Early Jurassic times?) probably associated with the opening of the Neuquén Basin, located farther south in northern Patagonia [1, 32]. Main evidences of this event are not regionally found, the best exposures outcrop in the Rincón Blanco Subbasin, however to the south, the subsurface Barrancas

Formation (Cacheuta depocenter) shares similar tectonostratigraphic characteristics with that of the Rincón Blanco but reveals certain uncertainties about its age. By the moment, this unit has been assigned to the Late Triassic [40] and even to Lower Jurassic [41]. The infill of Synrift III is represented by an alluvial-fluvial succession developed under renewed mechanical subsidence of the basin and marked semiarid conditions.

The final thermal relaxation of the basin seemed to have occurred during Jurassic and Cretaceous times and aborted during Tertiary times when the lithosphere undergone flexural subsidence induced by the Andean orogenic overloading and by sediment charge.

3. Puntudo Subbasin

The northernmost exposures of the continental Triassic Cuyana Basin crop out at the Cerro Puntudo locality on the western flank of the Precordillera in the San Juan province (Figure 3). These exposures record the sedimentation near the northern end of the basin related to a fault tip end. An angular unconformity separates de Cerro Puntudo succession from the underlying Choiyoi Group volcanics and it is tectonically truncated at top [34].

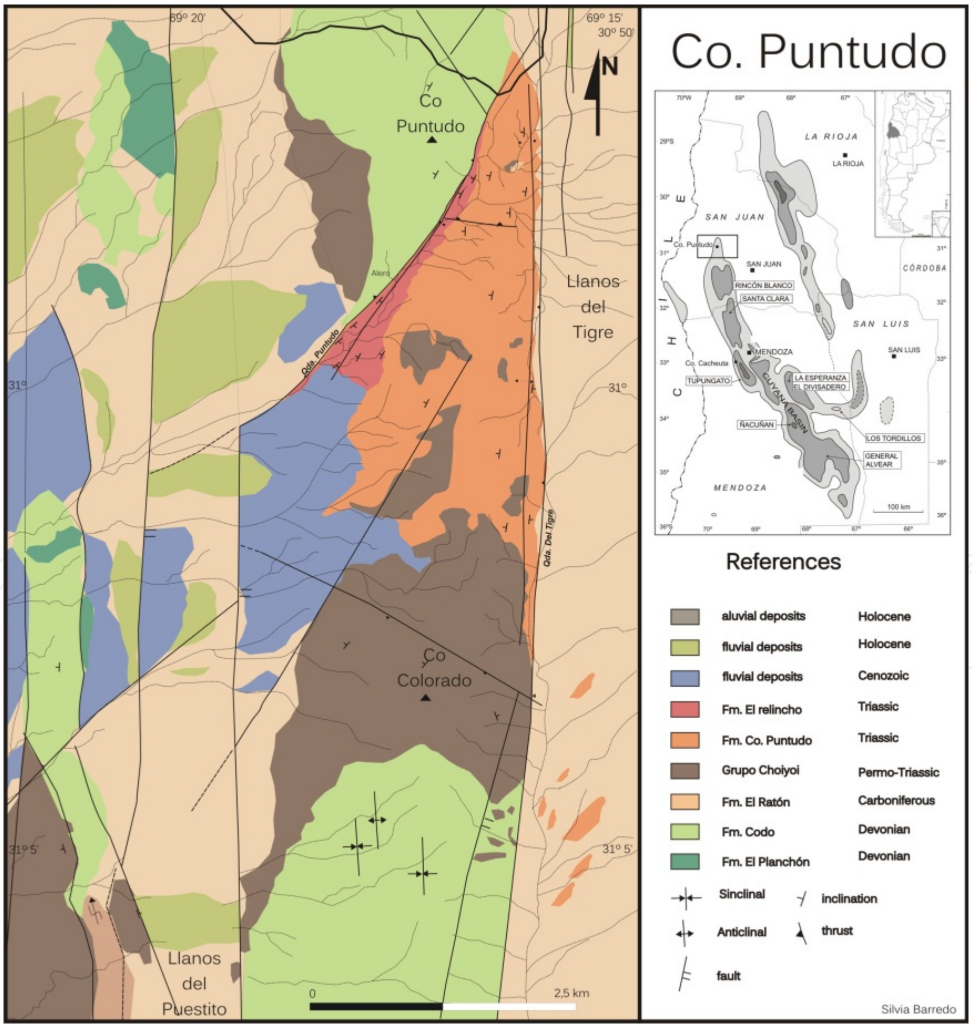

Figure 3. Geological map at the Co. Puntudo area. Modified from Mancuso [34]

The present structure consists of east verging (Andean) thrusts with wavelengths of ~1 km. These thrusts are responsible of the truncation and suppression of the west El Relincho facies (El Puntudo fault) (Figure 3). Triassic basin inversion was positive and topographic uplifting and gently folding of the ancient trough has been observed. The deposits are folded in northeast striking asymmetric syncline with its eastern flank well developed and the western almost truncated. The anticline of the eastern margin is interpreted as a result of reactivation of ancient rider blocks as a post depositional anticline during reverse motion of the structure. West-northwest faults seem to follow the Paleozoic fabric and are parallel to the Rincón Blanco Sub-basin transfers and thus, genetically related [9].

The extensional structure consists of a north-south striking fault (border fault?) located to the east. This assumption is based on the thick fan-conglomerates with main paleocurrents showing a marked southwesternward component of the flow parallel to the basin margin and towards the fault zone centre, where subsidence favoured the insertion of a shallow lake. This flow direction can be linked southernward with the axial sediment system of the Rincón Blanco Sub-basin. The border fault is presumed to be a west-dipping structure, probable lystric in cross section, with highest displacement to the center (displacement estimates are of 400 meters). On the basis of the maximum sequence thickness the “border fault” has been 12 km long. A notable reduction of the sedimentary record to the north and south can be extracted of the onlapping of the synextensional strata over basement rocks, particularly in the southern part where at the Cerro Colorado the Choiyoi volcaniclastics are exposed. Paleocurrents in this area points to a northward flow and thus, has been interpreted as an accommodation zone (transfer) that kept this depocenter probably disconnected from the Rincón Blanco Sub-basin.

The Triassic column reaches an exposed thickness of approximately 400 meters and has been divided into two units, the Cerro Puntudo and the El Relincho formations [42] arranged in two of the three synrift cycles recognized for the Cuyana Basin. The first tectosedimentary sequence or Synrift I corresponds to the Cerro Puntudo Formation. It is a fining-upward succession which starts with a thick package of 400 m alluvial fan conglomerates and cross-bedded coarse sandstones (Figure 4). This succession is mainly composed of an alternation of massive red clast-supported conglomerates and subordinated sandstones which passes upward to a braided fluvial system dominated by red and reddish-brown conglomerates and sandstones. Sheet-floods related to ephemeral fluvial deposits, characterized by red fine-grained sandstones, mudstones, and light-coloured tuffaceous limestones, are interfingered and cover the braided fluvial beds. The upper one-third of this first cycle comprises 75 m thick well-stratified and laterally persistent gray micritic and stromatolitic limestones, reddish brown mudstones, red fine-grained sandstones with rippled lamination, and thin levels of green tuffs interbedded. This part of the section was interpreted as deposited in a relatively shallow carbonate-rich lake with marked cyclicity recognized by a succession of retrograding and prograding events. Coeval volcanism is represented by the interbedded tuffs. To the southeast, the lacustrine deposits are dominated by siliciclastic facies made of reddish brown mudstones, red fine-grained sandstones, and green tuffs which were interpreted as deposited in a mudflat environment e.g. [23, 24, 34]. The climatic conditions during the deposition of the first synrift phase were markedly seasonal, as represented by the cyclical nature of the lacustrine deposits, not associated to tectonic controls. Palynomorphs suggest the presence of a relatively diverse flora composed by at least riparian vegetation (ferns and lycopsids) associated to the lake margins and a forest (araucariaceans) in the fluvial floodplains [34]. Due to the lack of evidence of evaporitic facies and extensive desiccation features humid climate conditions developed at least seasonally thus a subtropical seasonally dry climate might be assume for the upper part of the first Synrift phase. A U-Pb SHRIMP zircon age of 243.8 ± 1.9 Ma (Anisian) obtained from juvenile magmatic zircons in a tuff interbedded with the lacustrine beds constrained the deposition of the Synrift I at Cerro Puntudo to the Early-lower Middle Triassic [34].This age is consistent with palynological data obtained from equivalent lacustrine levels.

The second tectonosedimentary sequence or Synrift II, is represented by the El Relincho Formation. It starts at the point where the lacustrine deposition is abruptly interrupted by the instauration of a coarse alluvial setting. The fining-upward El Relincho succession (approx. 140 m thick) is dominated by green clast-supported conglomerates exhibiting clasts of the underlying Cerro Puntudo sequence. The succession passes upward into reddish brown, cross-bedded, coarse to medium -grained sandstones of braided fluvial origin. The upper limit of the Triassic succession at Cerro Puntudo area is tectonically truncated

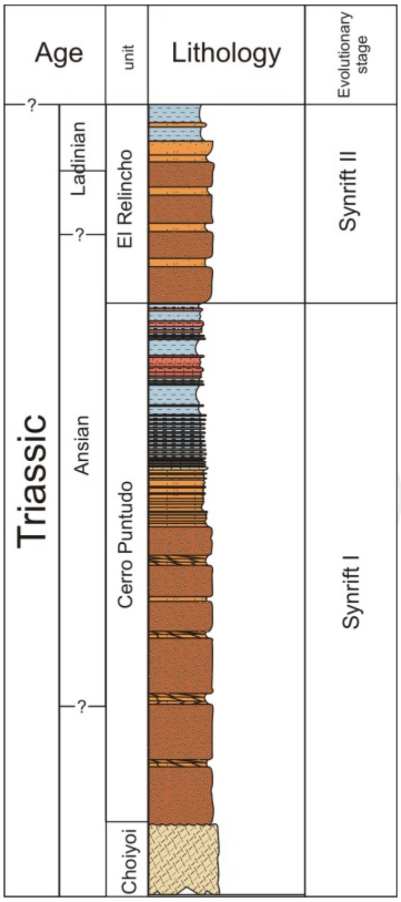

Figure 4. Generalized stratigraphic column of the Puntudo subbasin infilling showing the rifting episodes recognized across the whole Cuyana Basin. Modified from Mancuso [34].

4. Rincón Blanco Subbasin

The Triassic Rincón Blanco subbasin is located in the Precordillera fold and thrust belt at 31° 24′ – 31° 33′ south (Figure 5). It is 40 km wide and stretches approximately ~60 km N-S. The subbasin was mainly developed over Ordovician-Silurian distal platform deposits and Carboniferous glacimarine diamictites and turbidites nevertheless, to the north the column overlies Permian marine platform clastics. The present geometry of the Rincón Blanco active margin is a north–south tight asymmetric syncline. The structural analysis indicates that the east margin has been truncated by a series of west verging back-thrusts since Cenozoic times. Basin marginal deposits have in places been removed by erosion or preserved in fault inliers. The western margin has undergone east verging Andean thrusts (Cenozoic) with wavelengths of 2 km, presumably older than the back-thrusts, that has separated de outcrops from the flexural margin of the depocenter. Only, the south-eastern portion of the active margin remains practically unaffected, although some inversion of earlier extensional structures has been noted (Figure 6). Flexural margin is represented by isolated outcrops and subsurface deposits and is presently separated by a basement high from the active margin. Inversion was positive and topographic uplifting and gently folding of the ancient troughs has been observed, in particular in the Cerro Bola-Cerro Amarillo region (southernmost outcrops). Classic basin-inversion structures consist of anticlinal folds and reverse faults, like the BF segment exposed in Cerro Amarillo. Post depositional anticlines and synclines formed during reverse motion along the reactivated faults. Minor inverse faults area associated with the backtrhusts, they are composed of fault bend, fault propagation, and detachment geometries. In the flexural margin they have also uplifted the ancient intrabasinal highs where sequences are drastically thinned or basement exposed (Figure 7).

The spatial arrangement of the architectural elements permitted to interpret this Triassic depocenter as an asymmetric trough with a hinged margin. Basin-scale morphology could not be determined precisely because Triassic outcrops are tectonically truncated except for the western margin that could be modelled in subsurface [31]. Faults have displacement magnitudes of 1000 m and sole into a subhorizontal detachment surface at about 10000 m deep, below which deposits are undeformed. Using the architecture and some features of the sedimentary record it was established that the border fault (BF) was composed of right-stepping, west-dipping, normal to oblique faults, separated by a transfer zones (see Figures 2 and 5) became hard-linked. In cross section they are lystric and in plan view sinuous with highest displacement toward the center (displacement estimates are of 2 km). The resulting half-grabens are supposed to have gradually grown in depth and length through time surrounded by uplifted footwalls as a consequence of the absolute upward motion during fault displacement and isostatic adjustment. They correspond to Cerro Amarillo/Rincón Blanco and Marachemill troughs, in the active margin; Barreal and Agua de Los Pajaritos, in the flexural margin.

Kinematic indicators and the orientation of diabase dikes suggest a NNE-SSW (Az 30°) extension direction for the depocenter and a N-S to NNW-SSE border faults strike [8,9]. Local transfers zones correspond to west-northwest (Az 112°), left lateral strike-slip faults interpreted to have been formed to accommodate differential extension within the depocenter (Figure 6). These faults can be associated with the Paleozoic fabric which consists largely of generally northwest-striking and west-northwest striking reverse and tranpresional faults [37, 43]. Intrabasinal highs produced by rotation blocks made up internal elevations relative to the rift flank and trough and, consequently, the flexural margin contained much thinner sequence of synrift strata (~1800 meters) [31] than the active margin (3000 meters).

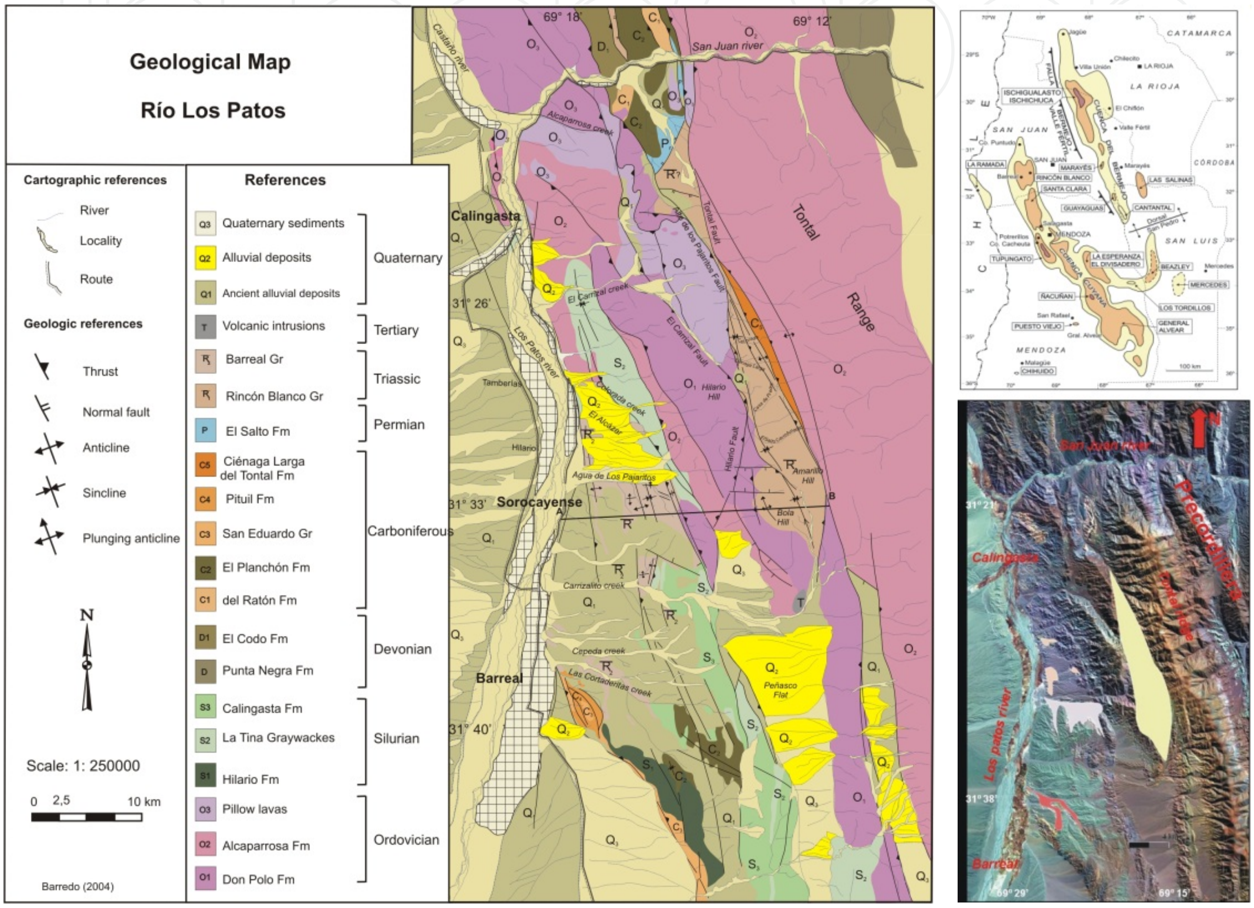

Figure 5. Left, geological map of the Rincón Blanco depocenter with detailed information from the flexural margin. Right, location map of the Rincón Blanco half-graben outcrops in the Cuyana Basin. The satellite image shows the distribution of the main depocenters, subsurface is not included. From Barredo [9].

The infilling consists of almost 3000 m coarse conglomerates interfingered with sandstones, shales, tuffs, tuffaceous mudstones and bimodal volcanic rocks composed of rhyolites and rhyiolitic tuffs and ignimbrites associated with the Choiyoi uppermost effusives [39, 45]. Alkaline basalts are also present but only in the flexural margin [9, 44]. The upper limit of the Triassic succession is marked by a regional uncomformity with the overlying Cenozoic foreland deposits. Three packages of genetically linked units bounded by regional extended unconformities of third order are associated with the three rifting stages (Synrift I, II and III) of the Cuyana Basin. These rifting stages beeing related with the acceleration of faults subsidence during Middle to Late Triassic. They comprise the Rincón Blanco and

Marachemill groups (active margin) and the Sorocayense Group (flexural margin) (Figure 7). Their evolution was mainly controlled by tectonic pulses but sediment supply and climate was also important [1, 9].

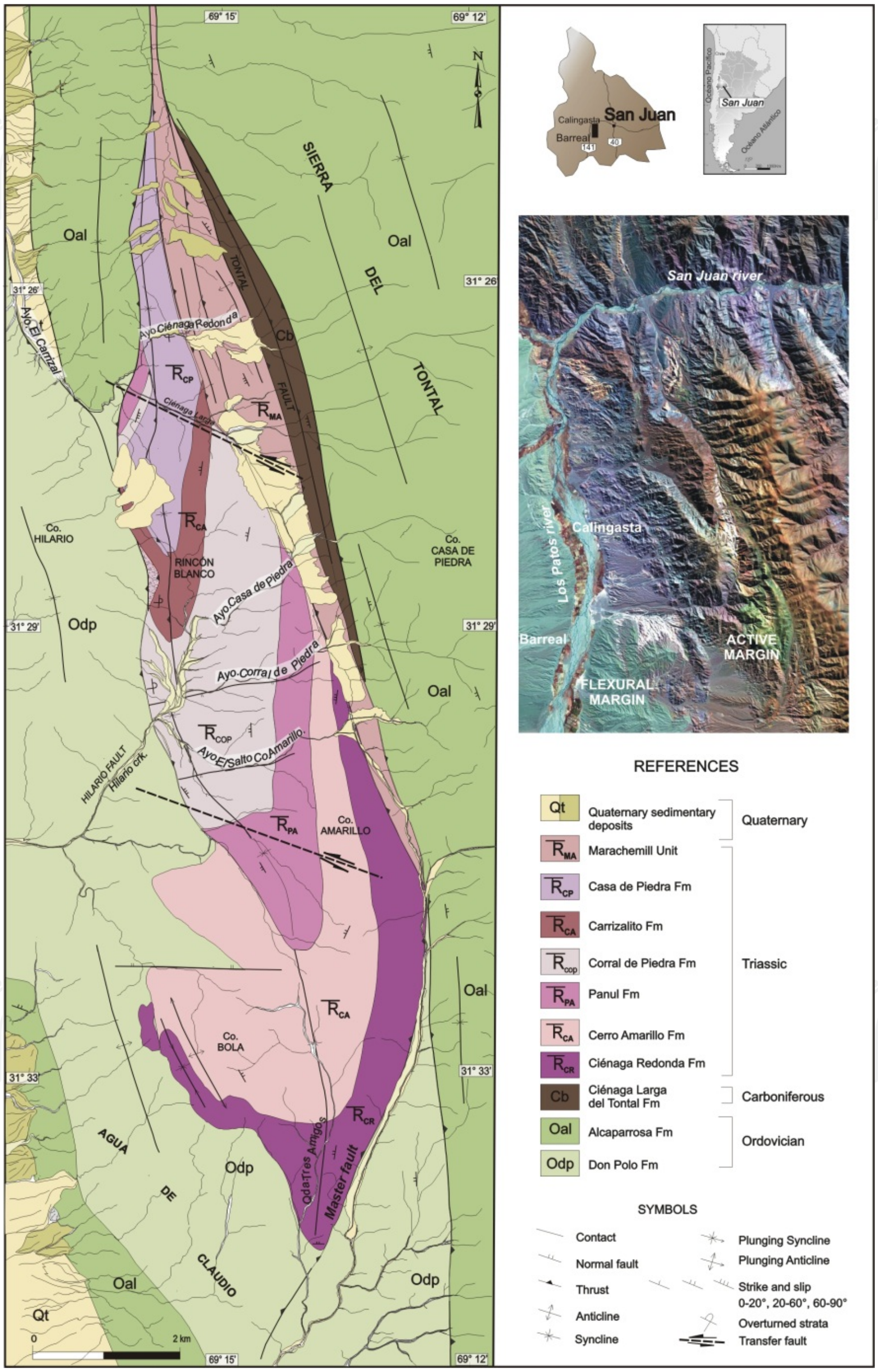

Figure 6. Detailed geological map of the active margin of the Rincón Blanco depocenter with inferred transfers faults. From Barredo [8,9].

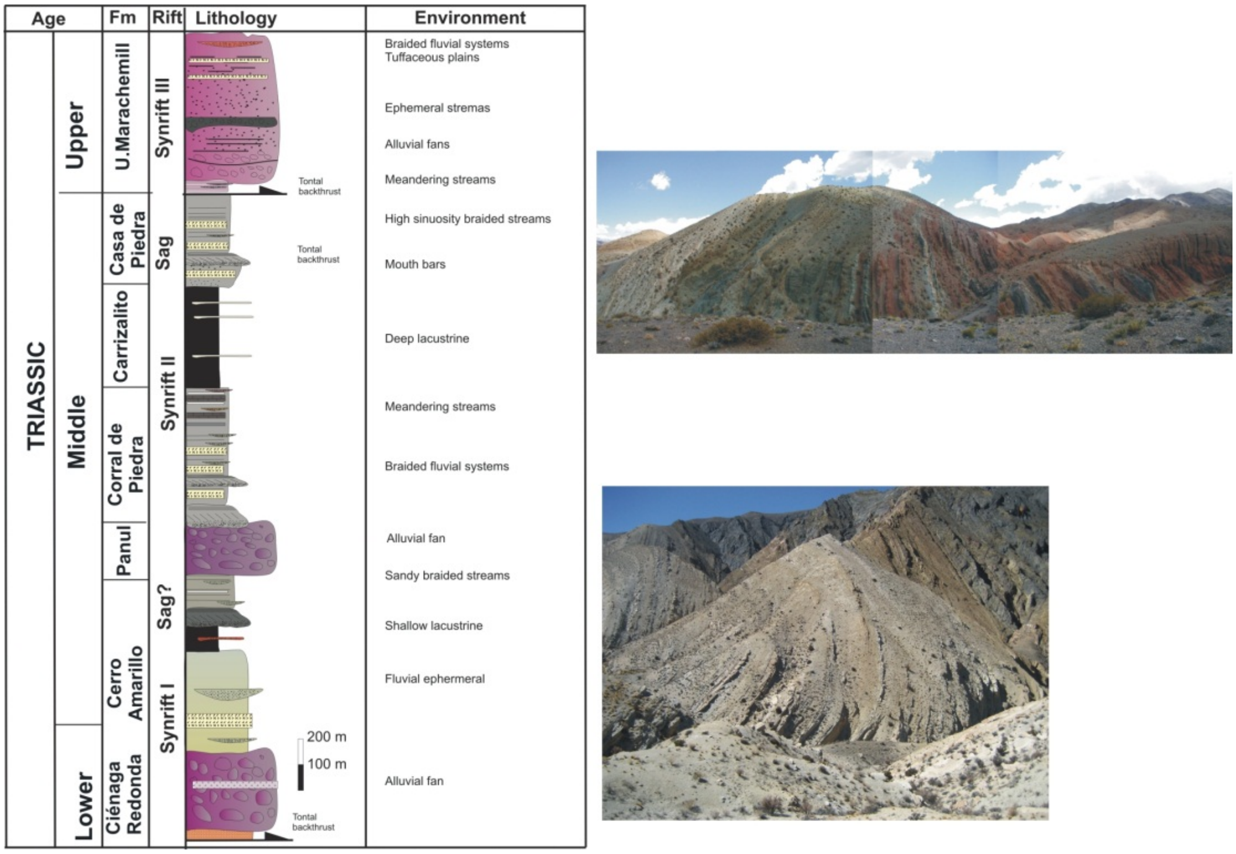

Figure 7. Stratigraphic column of the Rincón Blanco active margin. From Barredo & Ramos [1]. Upper right, north view of the coarse facies of the Marachemill Unit. Lower right,north view of the deep lacustrine facies of the Carrizalito Formation.

In the active margin, the Rincón Blanco Group is composed of, from base to top: the Ciénaga Redonda, Cerro Amarillo, Panul, Corral de Piedra, Carrizalito, and Casa de Piedra formations [15]. The trace of the contact between the synrift sediments and the prerift rocks is concave and well exposed to the south, in the Cerro Bola region (active margin). The Ciénaga Redonda and Cerro Amarillo formations correspond to the Synrift I, when the basin constituted a simple fault-bounded through, and comprise three facies association, alluvial fans, alluvial fans braidplain settings dominated by ephemeral streams, and shallow, mostly ephemeral lacustrine deposits. A maximum of 1200 m has been measured nearby the Amarillo and Bola hills (Figure 7) decreasing to the north to reach in outcrops less than 100 meters. This thickness diminishing is also observed to the west. The Synrift I starts with conglomerates and breccias interpreted as cohesive debris flow of fan deposits and un-cohesive debris flow developed in non-canalized sheetflows (Ciénaga Redonda Formation). Interfingered with these facies, there are ignimbrites and scarce rhyolitic tuffs and tuffs with an estimated age of 246 Ma [32]. Overlying, there are laterally discontinuous sheet-like beds of massive and horizontally bedded sandstones stacked in few meters with alternating conglomerates of the Cerro Amarillo Formation. This sequence corresponds to short-lived, wide, poorly canalized flows or low energy sheetflows in ephemeral streams of fans and bajadas. More distally, these systems are associated with silty-sandstones, massive to parallel mudstones with desiccation cracks and anhydrite lenses alternating with black (lignitic?)

shales deposited in a shallow lacustrine environment. This succession is covered by sandstones, shales and tuffs of braided fluvial origin with a predominantly axial paleoflow influx.

The Synrift II is separated from the underlying units by a regional unconformity and is composed of amalgamated conglomerates with angular basement derived lithologies, sandstones and ryolithes from the underlying Triassic units [9]. This sequence passes upwards to lenticular bodies of massive to trough-cross conglomerates and pebbly sandstones with erosive bases. They correspond to alluvial fan and braided fluvial facies association. The volcaniclastic content is notoriously high compared with the underlying units and consists of tuffs, and tuffaceous sandstones and conglomerates (Panul Formation). Fining–upward tabular sequences of fine conglomerates to sandstones with trough-cross bedding, lag deposits, and erosive bases follow. They grade to medium fine-grained, moderately to well sorted tabular sandstones/tuffaceous sandstones, reworked tuffs, and thick overbank mudstones at top of meandering fluvial origin (Corral de Piedra Formation). The whole succession passes vertically and laterally into the lacustrine facies of the Carrizalito Formation composed of thick massive mudstones/tuffaceous siltstones with volcaniclastics, mostly chonitic, levels. Upward these beds are covered by thinly stratified silty sandstones and massive mudstones related to the deeper facies of the lake. They are associated with massive or horizontally laminated marls (30 cm in thickness) and pale-grey organic levels which consist of laminated bituminous shales (oil-prone coals) with micritic calcite. The lake deposits are covered by clast supported planar to trough-cross bedded lenticular conglomerates and sandstones interbedded with laminated mudstones and limestones interpreted as deltaic mouth bars deposits (basal levels of the Casa de Piedra Formation). Upward these facies are covered by lenticular conglomerates and sandstones with trough-cross bedding and erosive bases of fluvial origin. They grade to fine-grained sandstones/tuffaceous sandstones and thick overbank mudstones which at top interfinger with ash fall tuffs.

A U-Pb Shrimp age on tuffaceous beds at the base of the lake levels of the Corral de Piedra Formation, in the Rincón Blanco depocenter, have yielded an age of 239.5±1.9 Ma [32]. This age constrains the initial deposits of Synrift II to the late Anisian (Middle Tiassic) which coincides with the recently date of 239.2 ± 4.5 Ma obtained by Spalletti [29] for the Potrerillos Formation (initial infilling of the Synrift II at the Cacheuta subbasin).

Finally, to the north-east margin of the basin a series of almost 900 meters of mainly volcaniclastic and clastic rocks were interpreted as the Marachemill Unit and included in the (Synrift III) [1, 32]. It is in tectonic contact with the Rincón Blanco Group through the Tontal backthrust (see Figure 6). Three facies associations characterized this unit: proximal to distal alluvial fans, ephemeral streams and fluvial systems. The first depositional environment comprises thick massive, mud-rich matrix-supported red conglomerates and breccias composed of volcaniclastic and sedimentary clasts mostly from the underlying Rincón Blanco Group. These facies interfinger with several ignimbrites and rhyolitic tuffs levels and tuffaceous sandstones. Poorly canalized flows and sheet floods developed in ephemeral environments follow upwards. They are characterized by coarse massive to horizontal laminated sandstones with erosive to sharp bases and shale intraclasts and are laterally associated with flood plain sandstones and shales with oxidized organic matter and desiccation cracks. Volcaniclastics are abundant and correspond to ash fall tuffs and pyroclastic flows. The third depositional environment corresponds to a braided fluvial system with conglomerates to granular sandstones in frequently amalgamated bodies. The conglomerates are poorly sorted with sub-angular to sub-rounded clasts from the Ordovician basement. Overlying beds correspond to tabular sandstones with planar cross stratification which grades to fine to medium sandstones with small scale trough-cross stratification and ripple-cross lamination capped by thin beds of massive or rippled greenish grey siltstones, tuffs, and mudstones with invertebrate burrows and mudcracks. Paleocurrents show an east-northeast predominant inflow. Ash-fall deposits are abundant constituting thick tabular massive, sometimes laminated, deposits and reworked levels that can be interpreted as tuffaceous plains with isolated poorly developed fluvial channels. U-Pb zircon age of 230.3 ± 1.5 Ma (SHRIMP) has been obtained for the Marachemill Unit suggesting an early Carnian age for its deposition [32].

The Sorocayense Group represents the infilling of the Agua de los Pajaritos and Barreal groups which correspond respectively to the north and south separated depocenters of the flexural margin [18,26]. The first is composed of: Agua de Los Pajaritos, Monina, Hilario, El Alcázar and Cepeda formations e.g. [46] (see Figures 5 and 8) and the other by: Barreal, Cortaderita and Cepeda formations [18]. The northern Agua de Los Pajaritos consists of a basal alluvial-fluvial sequence with abundant subaerial volcanic tuffs and volcaniclastic rocks overlain by deep lacustrine facies and fluvio-deltaic facies (Monina Formation) [46, 47]. Clast-supported conglomerates and breccias dominate at the base and are interpreted as non-cohesive debris with subordinate matrix-supported paraconglomerates (cohesive debris flow). Non-canalized and channelized levels follow, the lower ones correspond to sheet-flows and are characterized by massive sandstones with high energy directional structures; the second and most dominant upward, consist of lenticular thin bedded conglomerates associated with extended and shallow channels. These facies are followed by finning upward sequences of cross-bedded mostly tabular sandstones, primary tuffs, reworked tuffs, shales and bituminous shales, deposited in a high sinuosity river setting with well developed flood plains (frequently obliterated by fallout thepra). These facies laterally interfinger and are covered by sandstones, marls with algae lamination and massive and bituminous shales. Sandstone and siltstones with wave and climbing ripple stratification and tangential cross stratification correspond to deltaic mouth bars. At top and intercalated are white and green fallout tuffs and chonites, massive or thinly laminated and sometimes indurated with siliceous replacement. The clastic dikes cut these lacustrine facies. The fluvial-deltaic and fluvial strata of Hilario Formation follow. They consist of thickening and coarsening upward units characterized by laminated mudstone and thin sandstone beds which pass into amalgamated sandstones beds with small scours and cross-bedded sets of sandstone and clast-supported conglomerates, sandstones and thin coaly layers arranged in a series of fining upwards units. Finally, the facies are replaced by lenticular shaped fining upward coarse tabular sandstones and shales of a fluvial high sinuosity environment. This clastic and volcaniclastic sequence resembles that of the Synrift II of the active margin (Rincón Blanco Group) and has been preliminary correlated with it [46]. Sandstones with erosive bases associated with clayed mudstones, tuffs, marls, limestones, and massive and rippled laminated sandstones of high sinuosity fluvial and palustrine environments are considered the base of the El Alcázar Formation. This succession unconformably overlies the Synrit II and has been assigned to the early post-rift [32]. Tabular multicolored shales with tuffs, subordinates sandstones, and massive lenticular conglomerates are interpreted as lacustrine facies with alternating mouth bar and turbidites deposits. It is gradually replaced by lenticular sand and conglomerate bodies associated with mudstones, tuffs of floodplain origin sourced from outside the rifted basin. Lava flows mostly tholeitic interfingers these facies [44]. A renew of the extensional regime (Rift III) gave place to the deposition of the fan derived clastics of the Cepeda Formation lateral equivalent to the Marachemill Unit of Rincón Blanco depocenter [1].

The Synrift I in the Barreal depocenter encompasses distal fans and fluvial braidplain environments followed by shallow lacustrine shales, mudstones, and tuffaceous mudstones and deltaic sandstones [48] (Figure 8). Braidplain environments consist of clast-supported, massive, sometimes normally graded lenticular conglomerates and breccias with basal sharp and irregular contacts associated with sandstones that show parallel or low angle planar cross stratification. These facies are followed by massive and thin laminated shales, fine current-rippled sandstones laterally related to silty to fine-grained sandstones interbedded in a heterolithic arrangement with coal fragments, interpreted as lacustrine deposits. This first synrift sequence is included in the lower half of the Barreal Formation.

The second synrift phase (Synrift II) is marked by the deposition of braided fluvial systems with lenticular to tabular beds of poorly sorted conglomerates with subordinates sandier lenses and more tabular planar cross stratified sandstones associated with fining upward channel fill sequences.

This succession is covered by lacustrine deep facies with bituminous shales and thin subordinate sandstones of mouth bars and turbidites deposits, and finally lenticular conglomerates and coarse sandstones of fluvial systems, probably high sinuosity sandy braided system (upper half of the Barreal Formation). The post-rift facies are represented by the Cortaderita Formation beds. It starts with tabular shales, tuffs, and massive and rippled wave laminated sandstones of lacustrine origin. This facies are covered by lenticular pebbly mouth bar sandstones that pass upward to conglomerates and sandstones arranged in lenticular bodies of sandy braided fluvial system, sometimes obliterated by cinder fall out. The succession finishes with the instauration of a high sinuosity river system with well developed flood plains. The Synrift III (Cepeda Formation) consists of amalgamated clast and matrix supported conglomerates of alluvial proximal fans composed of volcaniclastics and siliclastics mostly from the underlying Cortaderita Formation; subordinate sandstones to the top of the conglomerates were interpreted as braided ephemeral plains. Sheet floods and poorly canalized flows developed in ephemeral environments with coarse massive to horizontal laminated sandstones with erosive to sharp bases and shale intraclasts. Volcaniclastics are abundant and correspond to ash fall tuffs. Upward, braided fluvial deposits of frequently amalgamated poorly sorted conglomerate bodies with sub-angular to sub-rounded clasts with subordinate sandstones cover the ephemeral facies. It passes upward to tabular sandstones with planar cross stratification which grade to fine to medium sandstones with small scale trough-cross stratification and ripple-cross lamination. To the top, massive or rippled greenish grey siltstones, tuffs, and mudstones with invertebrate burrows and mudcracks dominate; this beds were interpreted as mudflat deposits.

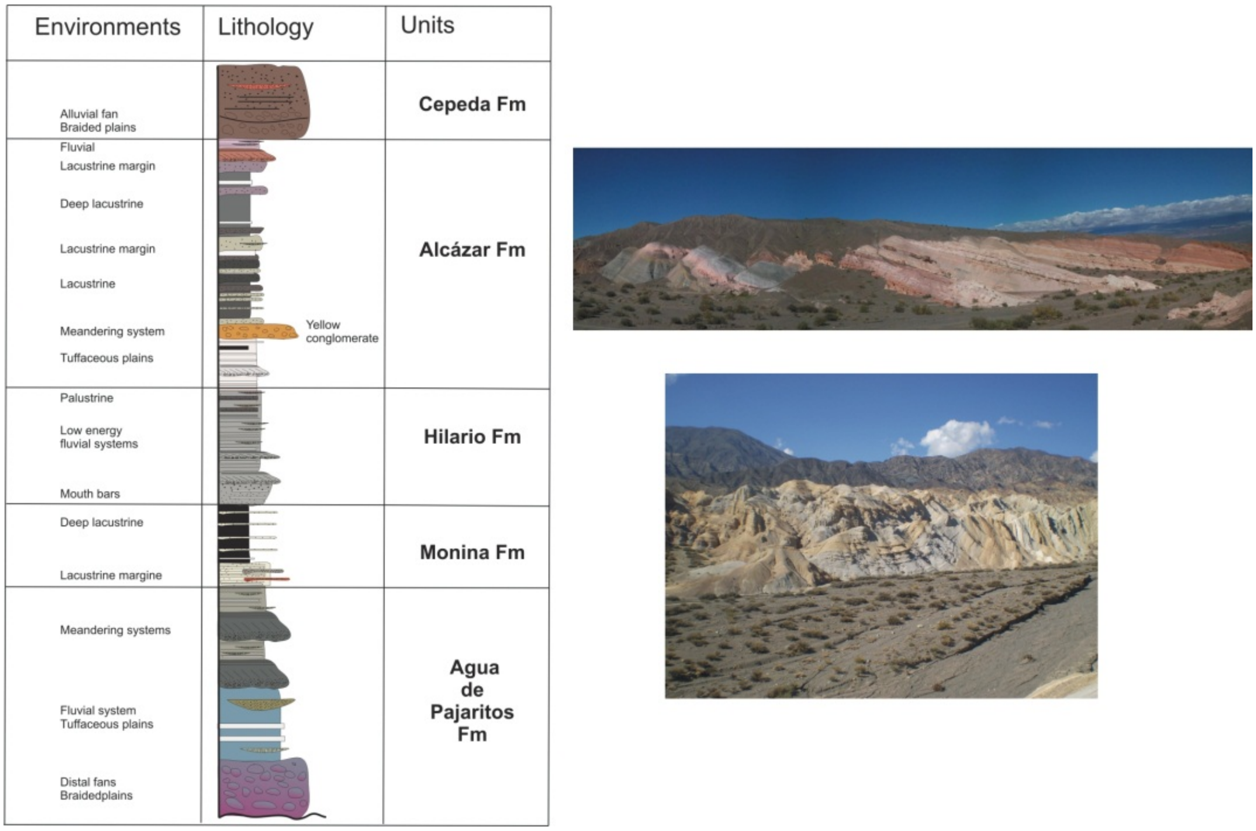

Figure 8. Stratigraphic column of the Agua de los Pajaritos depocenter (flexural margin). From Barredo [46]. Upper right, a south view from the El Alcázar postrift facies of clastic and pyroclastic materials deposited in shallow lake and fluvial environments. Lower right, east view the deep lacustrine Monina Formation.

Paleofloristic analysis based on the macrofloral remains preserved nearly in the whole column on both the flexural margin and active depocenters indicate the presence of evergreen subtropical floras adapted to seasonally dry climatic conditions in the Synrift I and lower part of Synrift II sequences. Thus, they do not indicate a marked climatic shift in this interval although floristic information from the uppermost part of the successions in this part of the Cuyana Basin is very fragmentary e.g. [26, 27].

5. Cacheuta Subbasin

The Cacheuta Sub-basin outcrops constitute the southernmost exposures of the Cuyana Basin. The best outcrops are located in the southern flank of the Cerro Cacheuta and in the nearby Cerro Bayo in the Potrerillos locality, west of Mendoza city (Figure 9). The eastern margin of the sub-basin was developed over Precambrian crystalline basement conversely; on the western margin the Triassic succession overlies Silurian-Devonian turbidites, Cambrian-Ordovician limestones, and the volcanics of the Permian-Triassic Choiyoi Group complex. A regional uncomformity determines the upper limit with the overlying Jurassic?–Cenozoic deposits.

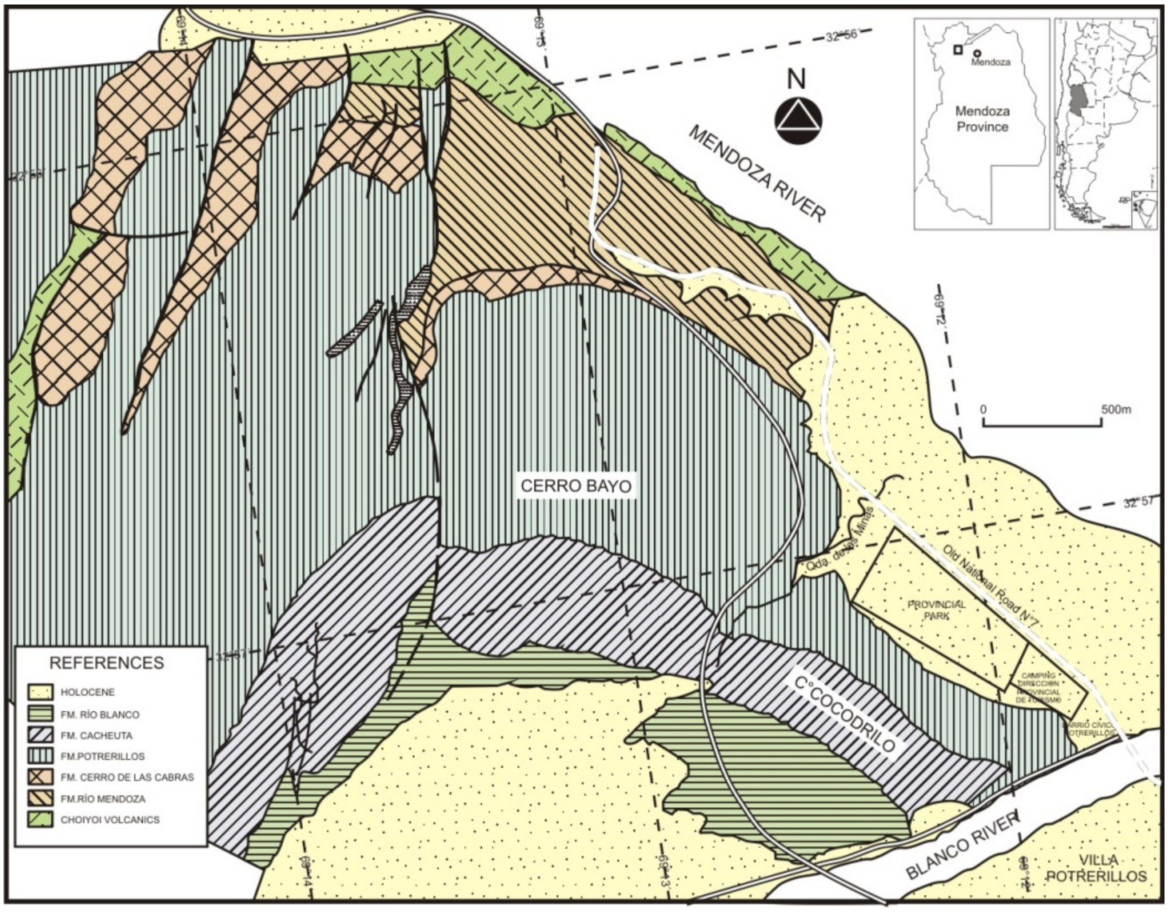

Figure 9. Geological map of the Cacheuta Subbasin outcrops at Potrerillos area. Modified from [49].

The Cacheuta Group represents the infilling of this through and is composed of, from base to top, by: the Río Mendoza, Cerro de las Cabras, Potrerillos, Cacheuta and Río Blanco formations. These facies characterizes two episodes of rifting followed by a period of post-rift subsidence. Unconformabling overlying these sequences, there is another unit, the Barrancas Formation of clear affinities with upper extensional events registered in the northern portion of the Cuyana basin. Up to the moment, it has been assigned a Late Triassic age by Rolleri & Fernández Garrasino [40] and a Lower Jurassic age by Reigaraz [41].

The structure consists of a series of N-NW to N-S trending asymmetric folds, broken locally by reverse high angle faults displaying either eastward or westward vergence [50] (Figure 9). These structures end against the Precordillera province to the north and extend far southeast to the San Rafael Block (see Figure 1). Tertiary structures encompass compresional Andean thrusts and positive inverted Triassic faults composed of folds and faults. Basement involved faults were mildly inverted and they still preserve extensional features. Minor antithetic and synthetic faults are release structures formed during bending. Compresional high angle inverse faults (60º) associated with the reactivation of Palaeozoic structures are also found.

The subbasin was narrow and asymmetric roughly triangular in cross section e.g. [13]. The more steeply inclined basin margin is located to the west and consists of a predominantly normal-slip fault/s associated with the border fault, which generally trends north–northeast. It is a steep dipping basement-involved structure with a hinged margin to the east. It coincides with an important Ordovician suture, the Valle Fértil Lineament [11, 12]. In cross section, it is lystric and in plan view it has been interpreted as being sinuous with highest displacement toward the center e.g. [7, 13]. Surface and subsurface information show that faults have displacement magnitudes of thousand meters and sole into a sub-horizontal detachment surface. Synrift sequences display reverse drag or rollover folds in subsurface. Strike-slip minor faults with a west-northwest strike and left-lateral slip can be observed in surface and subsurface. They were interpreted as inverted Permo-Triassic oblique-slip normal faults with dextral displacement. Intrabasinal highs produced by rotation blocks made up internal elevations relative to the rift flank and trough. In this way several sub-depocenters with local control were developed and limited by oblique structures to the border fault. They correspond to transtensional structures with north-northwest to northwest trending sinistral high-angle faults (60º and 90º to the northeast); additionally, northwest dextral lateral structures were also found. The Potrerillos area corresponds to a displacement transfer zone in which sinistral strike-slip meso-scale faults play an important role. It was a topographic high that separated this sub-basin from the Las Peñas through to the north. In this case, longer north–northeast-striking border fault (BF) of the Cacheuta depocenter is connected by shorter segments to the northern depocenter border by an opposite dipping fault. It has been interpreted as a soft linked connection as faults transferred displacement from one segment to another without being physically connected [9].

The Triassic column in this depocenter is of approximately 3000 m thickness (Figure 10). During the early depositional phase (Synrift I), the succession (approx. 800-1000 m thickness) is characterized by reddish conglomerates of alluvian fan facies (Río Mendoza Formation) related to the active margins of the rift. They laterally interfinger with multicolored mudstones, fine-grained sandstones, and tuffs of ephemeral-fluvial and playa-lake origin deposited basinward. In the depressed areas of the subbasin, shallow lake facies were accumulated characterized by the deposition of relatively thin oolitic grainstone beds and stromatolitic limestones interbedded with tuffs (Cerro de las Cabras Formation). This first sequence is separated by a regional unconformity by the second depositional phase (Sinryft II) [9, 13, 40]. The second synrift sequence (Synrift II) is a fining-upward succession (Potrerillos and Cacheuta formations) mainly represented by lower energy facies and fine-grained deposits than the underlying sequence. It was accumulated on a smoother relief due to the infilling of the depocenter and the deposits reach up to 1200 m in thickness. The Potrerillos Formation is characterized by fluvial conglomerates at the base intercalated with light greenish cross-bedded sandstones, and light tuffaceous sandstones of perennial braided river origin; this fluvial deposits grade basinward to greenish-grey laminated siltstone and sandstones interbeded with black bituminous shales and tuffs, related to high-sinuosity river systems. This facies laterally interfinger and are covered by the widespread lacustrine black shales of the Cacheuta Formation. In the maximum transgression of the lake, the lacustrine facies overlaps the fluvial deposits of the Potrerillos Formation to the basin borders. Finally, the post-rift phase in the depocenter is characterized by the red sandstones, mudstones, and tuffs of the Río Blanco Formation. This succession (up to 1000 m) has an onlap relationship with the underlying beds and represents the instauration of a fluvial-deltaic system over the lacustrine black shales. The Barrancas Formation (100 m) completely developed in subsurface, is composed of distal alluvial to fluvial facies stacked in amalgamated bodies developed under a semiarid climate [51]. It unconformable overlies the Río Blanco Formation and is overlain by Middle - Late Jurassic basalts of Punta de las Bardas Formation.

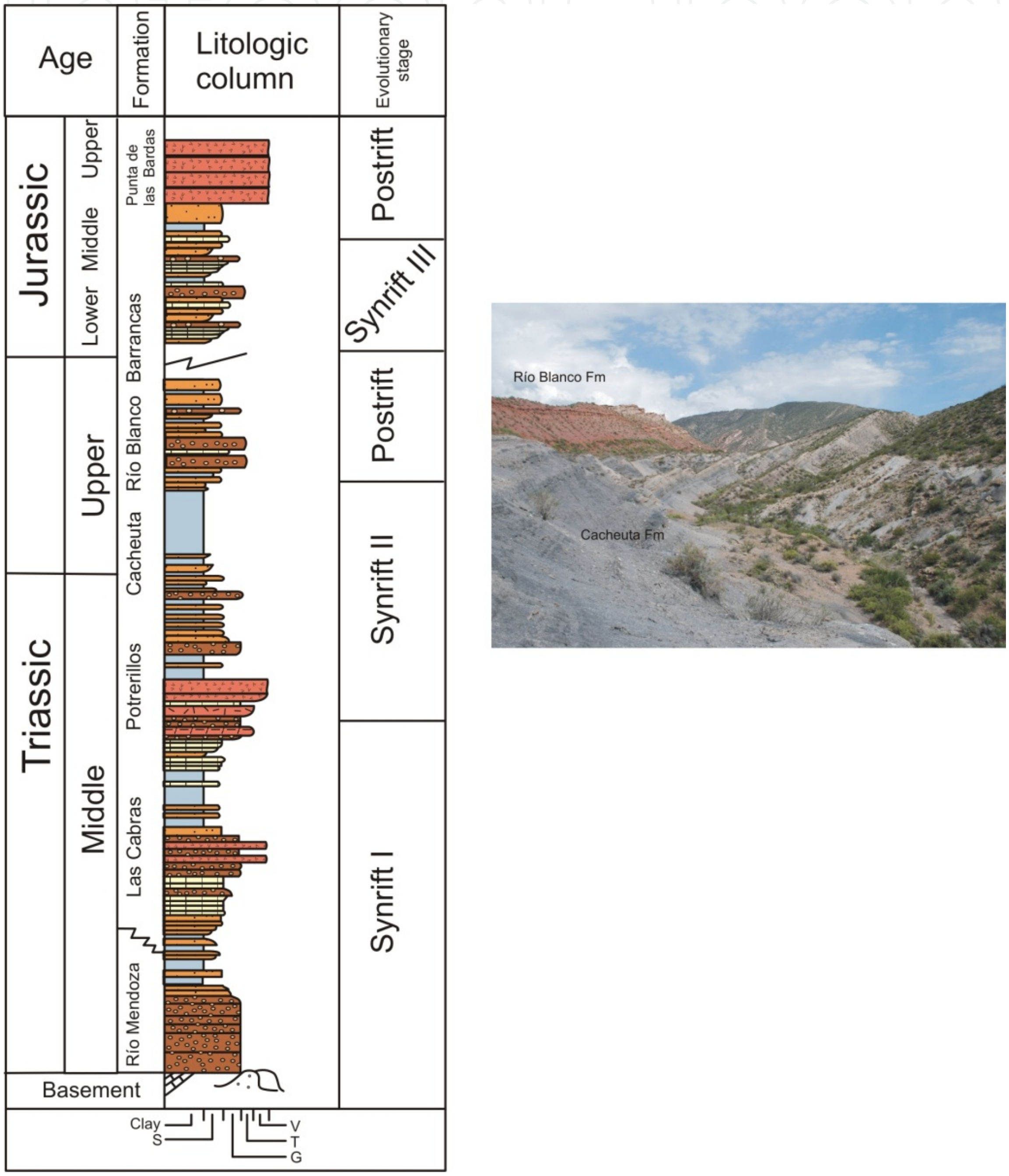

Figure 10. Proposed stratigraphic column of the Cacheuta sub-basin infilling showing the rifting episodes recognized in this work for the whole Cuyana Basin. Modified from Kokogian [13]. To the right, detail photograph of the Cacheuta lacustrine facies and the transition to the postrift facies of Rio Blanco Formation.

Paleofloristic analysis on the macrofloras preserved nearly in the whole column indicate the presence of subtropical floras adapted to seasonally dry climatic conditions. Moreover, the flora preserved in the Potrerillos and Cacheuta beds are evergreen forests in contrast with that represented in the ovelying Rio Blanco Formation that is characterized by a deciduous forest. This change indicated a climatic shift to dryer conditions during the deposition of the fluvial redbeds of the Rio Blanco unit e.g. [27].

Recently, U-Pb SHRIMP ages on tuffaceous beds of the top of Cerro de las Cabras and the base of the Potrerillos formations have constrained the initial infilling of the Cacheuta subbasin (Synrift I) and the beginning of the Synrift II to the early Anisian and the Anisian-Ladinian boundary, respectively [29, 33]. This age is coincident with that recently obtained from the lacustrine beds at the top of the first synrift stage in the northernmost exposures of the Cuyana Basin at Puntudo [34].

6. Geodynamic and tectonosedimentary evolution of the Cuyana Basin

The depositional sequences of the Cuyana Basin resulted from the complex interaction of the supply of sediments, the availability of the accommodation space (both with tectonic components), sea level variations and climate variations. The main control on basin geometry was the deformation field resulted from the tectonic activity along the margin of Gondwana. In this sense, fault geometry provided the final morphology of the trough and its resulting subsidence, which in term controlled the sedimentation rate, grain size, channel migration, avulsion episodes and the development of lacustrine environments.

The Gondwana continental margin has been created as a result of the accretion and amalgamation of different continental blocks and allochthonous terrains to the South American proto-margin since the Proterozoic times up to even the Early Paleozoic e.g. [52 to 55] (Figure 11). This tectonic cycle terminated as a consequence of the Sanrafaelic orogeny [56] with the formation of a magmatic arc in the Late Carboniferous-Early Permian times [58, 57]. Following this deformational event and during Middle Permian to Early Triassic times, an important silicic magmatism episode occurred associated with an extensional period. It was named Choiyoi Group [58] and was interpreted as the result of the collapsed of the Permian orogen e.g. [36, 4, 38, 59] probably because of the declining and/or cease of the long-lived subduction of the Panthalassan margin [59].

Additionally, and on the basis of the strain analysis, several authors suggested that these extensional forces could have been related to the beginning of the Pangea breakup e.g. [36, 60, 61]. Zerfass [62], proposed a regional uplift due to oblique compression for Lower to Middle Triassic times which is somehow in agreement with the geodynamic contest envisioned by Llambías [63] for the basement of the Neuquén Basin, except for the thermomechanical parameters that could have triggered this upwelling, for these latter authors suggest the probable influence of a thermal rise and/or slab brake off. According to Zerfass [62] scheme, the basal Talampaya and Tarjados formations, corresponding to the Ischigualasto Basin (see Figure 1), would constitute together a second-order sequence and could be separated of the tectonic history of the basin. By MiddleTriassic - Early Jurassic times however, the inception of a new juvenile magmatic arc associated with the renewal of the subduction processes, added extra intraplate extensional forces [63 to 65]. Consequently, rapidly subsiding, fault-bounded, narrow back arc-related troughs were formed and arranged in an *échelon* pattern like the Bermejo, Ischigualasto-Villa Unión-Marayes and Cuyana, basins (see Figure 1) e.g. [11, 32, 66]. Charrier [67], Criado Roque [68], Spalletti [26] among others, and more recently, Milani & De Wit [69] have proposed a transtensional origin for Triassic basins related to a sinistral shear zone along in the western plate margin. According to the latter authors, this transtensional regime could be related with the geodynamic processes occurring in a still active Gondwanides orogen. By Early to Middle Jurassic times subduction was completely restored and a huge extensional regime were developed thereafter in the backarc [3, 70, 71].

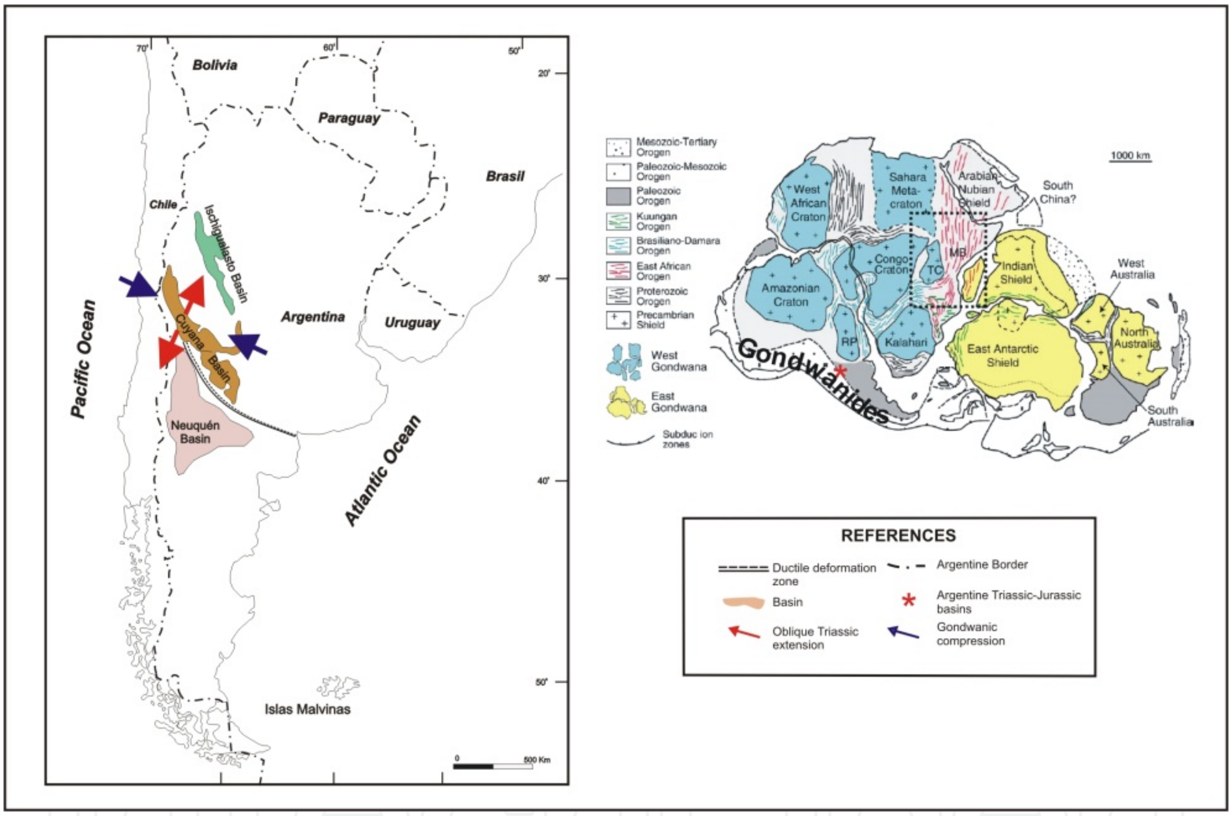

Figure 11. Regional Map of the distribution of the Triassic-Jurassic basins of Argentina. Arrows indicate stress direction, in blue main compressional regime during Upper Carboniferous-Lower Permian and in red oblique extensional regime during Middle to Upper Triassic times. Right, pre-break-up Gondwana configuration taken from Corti [82]. See red asterisk for basin location.

The Cuyana Basin is a NW trending rift whose Triassic record reaches 3700 meters [9]. Its origin has been associated with an oblique extensional regime (Az 35°) [9, 72] which reactivated the northwest-striking lithosferic weakness related to the ancient Gondwanan sutures e.g. [3, 53, 73] (Figure 11). In this scenario, work hardening of the lithosphere by repeated deformational events during the Palaeozoic along the Gondwanides led to an increase in the lithospheric strength and together with the obliquity of the extensional regime, gave place to a north to south trend o basin formation. Accordingly, the Bermejo Basin and

Ischigualasto-Villa Unión-Marayes basin opened first in Early-Late Triassic [74] followed by the Cuyana Basin, during the Middle Triassic [32] and south-westward in northern Patagonia, the Neuquén Basin during the Late Triassic–Early Jurassic times e.g. [63]. Similar extensional events have been recognized along the cratonic areas of southern Brazil by Hackspacher [75] and Zerfass [62].

An oblique subduction along the Panthalassan margin has been proposed by Martin [76] for the Permian–Triassic times which account for the obliquity of the extension as lateral upper crust shear. Considering that the Gondwanides basement is composed of a series of different crustal domains with distinct mechanical characteristics [77] and which together are different from that of the cratonic region, the stress transmission from the this belt to the backarc and foreland regions could have had shear components with different magnitude along strike. In this sense, several authors like Llambías & Sato [59, 38, 78], among others, proposed that during Permian times continental crust block rotation along the Gondwana margin took place leading to a reorganization of plate boundaries and plate kinematics, especially along the Triassic.

In the particular case of the Cuyana Basin, Middle Triassic extension took place under a relative high thermal flux of about 70 mv/m^2 [31, 39] which affected a normal to thinned crust of 30 km thick. Magmatism was due to decompression and melting of the asthenospheric mantle driven by intraplate stresses and lithospheric thinning and probable by the influence of a thermal rise during slab brake off [63, 79]. It constituted an alkaline bimodal suite initially acidic because of crustal melting, and then basaltic and probably sourced from the base of the lithosphere while subduction was in progress by Middle to Upper Triassic [39].

Faults reflect the historical sequence of changing stress regime during Triassic times in the Gondwana margin. Some of these structures reactivated ancient preexisting weakness zones like the Paleozoic sutures within the Gondwamides. In the beginning of extension the limited crustal extension led to the formation of a series of restricted half-grabens separated by transfer faults which apparently follow a the Paleozoic fabric e.g. [9, 12, 37] or intrabasinal highs. Extension persisted up to Jurassic (Cretaceous?) times with at least three remarkable pulses of fault reactivation which are well preserved in the Rincón Blanco subasin; while in the Cacheuta depocenter there are still doubts. The Barrancas Formation has been considered of Late Triassic age by Rolleri & Garrasino [40] using cyclostratigraphic concepts or Early to Middle Jurassic age by Regairaz [41] on the basis of field relationships. The existence of Late Jurassic to Early Cretaceous basalts (Punta de las Bardas Formation) over unconformable overlying this unit made several authors to considered Barrancas Formation as Jurassic. In any case, enhanced extension during westward migration of the magmatic arc [63] and the final insertion of the subduction complex with negative trench roll back and probable extra thermal flux governed the deposition of this unit and de evolution of Punta de las Bardas basalts. Further north, the Marachemill Unit could be considered the initial signs of this renewed extensional event of the Gondwana margin.

The Cuyana Basin was filled with a tectonically induced second-order thick pile of continental deposits arranged into three third-order sequences. These are composed of alluvial, fluvial, lacustrine, deltaic and pyroclastic deposits [1, 32]. The switch from major fluvial to lacustrine environments along the basin is interpreted to reflect a change in tectonic activity. These third-order depositional sequences can be correlated with those of the Santa María Supersequence (Paraná Basin-Southern Brazil) [62].

Depocenters in the Cuyana Basin are half-grabens roughly triangular in cross section. The border fault (BF) consists of a network of mainly normal to oblique-slip faults which are in plan view soft linked and separated by strike-slip minor faults (Cacheuta and Rincon Blanco/Santa Clara) or by breached relay ramps (Rincon Blanco-Puntudo). Only between the southern and northern segments are inversion of segment polarities. Fault-displacement folds were formed and locally influenced sedimentation, with synrift units thickening in the synclinal lows and thinning onto the highs in the footwalls. This situation produced the wedge-shaped sedimentary units that can be traced through the depocenters in the field and subsurface. The high dip angle of the border faults controlled the significant amount of throw, especially of the Cerro Amarillo area (Rincón Blanco depocenter) with an initial infilling of 1200 meters. The footwall of the border faults were uplifted in response to absolute upward motion coupled with the isostatic unloading. In the particular case of the Rincón Blanco depocenter this topographic high, with the slope to the east, gave place to the erosion of the basal Choiyoi deposits, so common in the Puntudo and Cacheuta depocenters. These shoulders prevented sediment inflow and streams entered the basin along the hinged margin but also axially mostly sourced by the transfers (Agua de Los Pajaritos and Barreal formations). The rift was not connected with the sea and so eustasy played no role in the basin infilling evolution, drainage systems were in fact controlled by local (mostly lake) base levels. In this scenario, the relationships among incremental accommodation space (mostly associated with tectonic subsidence), sediment+water supply and short-time climatic influences determined which depositional system predominated. When the sediment supply exceeded the incremental accommodation space (basin overfilled), during first stages of rifting, alluvial to braidplain deposition predominated with strata progressively onlapping the hanging-wall (Cerro Puntudo Formation, Ciénaga Redonda and Río Mendoza formations). These deposits occupied a narrow band close to the main faults and transfers, and were coeval with the latest tholeitic magmatism (Choiyoi Group) from a Cisuralian Magmatic arc [33,39].

The gradual faults growth in length and displacement drove depocenters to increase in depth, length, and width and thus, the incremental accommodation space through time. In this way, they were underfilled with small drainage systems entering from footwall region between border faults or from the fault tips where footwall uplift was minimal. The main fluvial systems were mostly axial or longitudinal (Cerro Amarillo, Cerro de Las Cabras and Cerro Puntudo formations). When the incremental accommodation space significantly exceeded the sediment supply and water input, shallow hydrologically closed lacustrine deposition (playa-type) predominated (Rincón Blanco and Cacheuta depocenters) and a carbonate-rich lake in Puntudo depocenter all of them with interbedded tuffs. These lakes were located close to the faults and subjected to climatic base-level fall-to-rise turnarounds and thus show a marked cyclicity. Climate was semiarid and seasonally humid. When the incremental sedimentation rate equalled the accommodation space rate climatic induced or, less probable, tectonic induced (early post-rift?) fluvial systems developed over these lakes. According to U-Pb zircon dating this tectono-sequence can be constrained to the base of the Anisian (early Middle Triassic) [32].

In Middle Triassic (Rift II) a significant reactivation of the faults gave place to the development of a regional unconformity that can be correlated across the three depocenters. It has been interpreted as being an intra-Triassic tectonic event, probably associated with the acceleration of the subduction rate on the west margin as a consequence of the reinsertion of the convergence [63]. It was responsible of the high sediment supply that gave place to the deposition of the alluvial-fluvial facies of El Relincho, Panul and the base of Potrerillos formations (Synrift II initiation). Fluvial to deep lacustrine facies developed when the accommodation space rate succeeds the sedimentation rate in a basin that widened significantly as it is suggested by numerous onlaps observed in all the troughs. Climate was sub-tropical and seasonally dry and lakes were balanced and deep (meromictic) with deltaic and fluvial deposition occurring around the margins. Climatic induced lake-level cycles are clearly seen in the stacked parasequences bound by lacustrine flooding surfaces which are superimposed on variable rates of subsidence of the rift border fault zone. Upward, the lacustrine–fluvial transition resulted from a decrease in incremental accommodation space and/or an increase in sediment supply once extension slowed in the post-rift stage (Casa de Piedra, Cortaderita and El Alcázar formations). The shoaling tendency of the lakes during this stage was due mainly to the basin growth which forced to spread the water over broader regions, drowning extended regions with the development of palustrine environments. Important ash fall tuffs and reworked volcaniclastics interfinger these postrift facies along the whole basin. This second tectono-sequence corresponds to the Anisian (upper Middle Triassic [32].

Another extensional event took place in Early Late Triassic (Rift III) [32]. At present, best exposures associated with this event are found in the Rincón Blanco Subbasin (Cepeda and Marachemill formations) [1, 32]. In the Cacheuta depocenter a tectosedimentary similar unit is represented by the Barrancas Formation, firstly assigned to Upper Triassic by [10]. However and on the basis of field relationships, Regairaz [41] proposed a Lower to Middle Jurassic age. Presently, there is no absolute dating for this unit but several authors like Rolleri & Fernandez Garrasino [40] using the sequence stratigraphy concepts could demonstrate its Triassic affinities. On a regional scale, the lack of Jurassic - Cretaceous strata in the northern portion of the Cuyana Basin (Puntudo and Rincón Blanco depocenters) likely suggests that it stopped subsiding while the southern portion of the basin were still active contemporaneously with the opening of the Neuquén basin with the deposition of the Barrancas and Punta de las Bardas formations [32]. Yet, it is worth mentioning that Jurassic levels have been described in nearby latitude in the Precordillera by Coughlin [80] and Milana et al. [81] which suggest that further studies are needed. In Southernmost Brazil and Uruguay, the Triassic Sanga do Cabral Supersequence was divided in three sequences [62] that can be also correlated with these stages. Proximal fans and braided ephemeral to perennial streams of semiarid, seasonally humid (?) climatic regime developed as a consequence of the lost of accommodation space and a high sediment supply. This tectono-sequence was assigned an early Carnian age (lower Late Triassic) in the Rincón Blanco trough by Barredo [32] but taking into account the evolution of the Barrancas Formation and Punta de las Bardas Basalts, of the southern Cacheuta depocenter, it could have spanned up to Jurassic (Cretaceous?) times. Subduction was definitely restored during upper Late Triassic-Lower Jurassic under extensional conditions associated with the westward migration of the arc e.g. [63]. The new extensional regime would have governed the evolution of the upper section of the Cuyana Basin whose final thermal relaxation should have occurred during Middle-Late Jurassic and Cretaceous times and aborted during Tertiary times when the lithosphere undergone flexural subsidence induced by the Andean orogenic overloading and by sediment charge.

7. Conclusion

The Gondwana continental margin has been created as a result of the accretion and amalgamation of different continental blocks and allochthonous terrains to the South American proto-margin during Paleozoic. In this scenario, Triassic continental rifts of Argentina settled sometimes controlled by the inherited fabric. Hence, a deep geodynamic analysis is necessary if we want to understand the evolutionary history of these basins. The uplifting and subsidence of different portions of the crust will control the insertion and development of sedimentary basins and the regional distribution of their infilling. In the Cuyana Basin, depositional sequences resulted from a complex interaction of the supply of sediments, the availability of the accommodation space (both with tectonic components), sea level variations (which also may have a significant tectonic influence) and climate variations, being the first-order control on basin geometry the deformation field resulted from the tectonic activity. Its origin has been associated with an oblique extensional regime which in some cases reactivated the northwest-striking lithosferic weakness related to the ancient Gondwanan sutures. The resulting sedimentary environments display significant differences across subbasins which made bio and lithostratigraphic correlations quite imprecise. Still, recent isotopic dating permitted to arrive to an enhanced evolutionary model when combined with thermo-mechanical analysis, cyclostratigraphy and tectonostrigraphic tools. A more precise model of the Cuyana Basin evolution now predicts that it was filled with a tectonically induced second-order thick pile of continental deposits arranged into three third-order sequences. These are composed of alluvial, fluvial, lacustrine, deltaic and pyroclastic deposits separated by key stratigraphic surfaces or sequence boundaries resulting from lacustrine flooding and/or forced regressive surfaces. The Synrift I contains volcaniclastic, alluvial-fluvial and saline lake deposits when accommodation exceeded sediment and water input. The Synrift II starts with alluvial–fluvial followed by deep lacustrine and deltaic environments under wetter climatic conditions. The Synrift III encompasses volcanic and volcaniclastic alluvial and fluvial dominated environments developed under semiarid conditions. These three stages are associated with the evolution of the Gondwana margin during Permo-Triassic times, when lithosphere undergone a wide spread extensional regime due to the almost cease of subduction, the collapse of the ancient Permian orogen and the reorganization of intraplate stresses during Pangea breackup (Rift I and II). The inception of a new juvenile magmatic arc associated with the renewal of the subduction processes, added extra intraplate extensional forces which gave place to a third regional scale event, the Rift III, which begun in Late Triassic and extended up to Middle Jurassic. The final thermal relaxation took place during Cretaceous when lithosphere undergone flexural subsidence induced by the Andean uplift.

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