Depositional Controls over the Lacustrine Source Rocks of the Cuyana Basin. An Approach to Model a Mechanical Cyclicity Through an Integrated Analysis of Sequence Stratigraphy, Petrophysics and Rock Properties

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Abstract

Integrating field and laboratory data is possible if there are strong geologic criteria to relate them. This challenge demands understanding rocks from the fabric and mineralogy up to the architectural elements of rock bodies at a basinal scale. The geological properties of rocks, being them clastic, chemical or biochemical, influence reservoir quality and hydrocarbon producibility, but continental mudrocks/siltstones (shales) are by far more complex because of their depositional nature and highly variable vertical and lateral sedimentary characteristics. Grain size variability and sedimentary structures are common in these rocks. From outcrops, well logs and the source rocks of the Cuyana Basin (Argentina) could be characterized as deposited in lacustrine environments under a strong tectonic and climatic influence. Silty sandstones, limestones, massive and laminated bituminous shales developed in underfilled and balanced to overfilled lakes. They display parallel/inclined/rippled laminations, coarsening/fining upwards patterns, nodules, scour surfaces and pedogenic features. Total organic content may reach 14 % and corresponds to macro and micro floral remains, freshwater invertebrates and kerogen types I and II. These lithofacies are vertically stacked in patterns that can be related to cycles with different mechanical properties. In outcrops and with the help of seismic lines third order depositional sequences representing basin variations in accommodation space were recognized as low accommodation (LAS) to high accommodation (HAS) sequences developed in each of the three rifting stages. Using detailed information about mineralogy and fossil content climate was characterized and fourth order parasequences could be characterized. Fifth order (bedset-rhythms) cycles were interpreted on the basis of outcrops and well logs. Inorganic (especially clays) and organic content, pedogenic fabric, burrows and microfracturing represent weakness planes and as they vary according to these cycles, it was possible to model a mechanical cyclicity along the whole lacustrine column and to analyze their depositional controls. This integrated study has provided relevant data for the understanding of the geological and mechanical properties that will contribute to the optimization of fracture programs.

Introduction

The need to increase hydrocarbon reserves challenges countries with a novel concept in oil prospecting. In this sense, new prospecting techniques help to understand the rock in a static and dynamic framework. Several geological processes, like deposition, compaction, petroleum generation, expulsion and migration (or not) and accumulation can be modeled using integrated tools from basin mechanics to sequence stratigraphy. Micro and Micro scale analysis involves the study of sediments —that encompasses, from an engineering standpoint, a multiphase system of mineral particles, rock fragments, bioparticles, etc.,— where the layout results in a porous structure that contains fluids such as water, hydrocarbons and gas. Deformation is here determined by multiple causes, mineralogy, and the existence of bioparticles, cements, and the interaction between individual particles, their intrinsic deformation, and the relative movement between them, orientation, and etcetera. Basin analysis helps understand how these large lithospheric structures — that contain hundreds of thousands of meters of sediment— where mechanically formed. When basins hold unconventional reservoirs associated with shales, the mechanical properties of the source rock must be studied, because it is at the same time reservoir, trap and seal, and its characteristically low permeability requires the use of certain extraction techniques that are complex, and therefore costly. The geological properties of these rocks are by far complex because of their depositional nature and highly variable vertical and lateral sedimentary characteristics which become even more variable in continental environments (Martinsen et al. 1999; Bohacs et al. 2000; Barredo 2012; Barredo and Stinco 2013, among others).

The 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. Its best exposures are located along both flanks of the Precordillera, in Mendoza and San Juan provinces (Fig. 1). At present, underlies a lowland segment of the Argentine foreland. It corresponds to a continental rift composed of several asymmetric half-grabens that were identified as Cacheuta, Las Peñas-Santa Clara, Rincón Blanco, Puntudo General Alvear, Ñacuñán and Beazley (Legarreta et al. 1993; Lopez Gamundí 1994; Spalletti 2001; Barredo 2004, 2012) (Fig. 1). The basin was filled with a tectonically induced second-order thick pile of continental deposits arranged into three third-order sequences. This non-marine record showed that seal level was not a factor influencing depositional patterns; instead it seemed to have been the interaction between tectonics (subsidence-uplift, propagation, interaction and linking) and climate influencing the accommodation space, sedimentation rate, water input and the biological evolution of lakes that are presently significant hydrocarbon source rock and possible unconventional reservoirs (Barredo 2012). A reasonable sequential interpretation model in this case would then be that of Martinsen et al. (1999), which apply the concept of stratigraphic base level or local base level, whose variation depends on the accommodation rate (A) in relation to sediment input (S). The accommodation mostly linked to tectonism, sedimentation, climate and hydrological variations. Thus, if $A/S \leq 0$, there is little space, and mostly a bypass occurs in the sedimentation with the development of significant erosion surfaces. It corresponds to the sequence boundary (SB). When $A/S > 0 < 1$ sedimentation takes place favored by the existence of space in the basin. In this case low accommodation sequences (LAS) are deposited and correspond to alluvial-fluvial to shallow lacustrine facies. Finally, if $A/S \geq 1$ the balance between sedimentation and space is exceeded and the basin remains underfilled. Depending upon climate, deep lakes or playa lake can be built which constitute high accommodation sequences (HAS). At the beginning of the post rift, when faults slow down or become no longer active, the inherited relief will contribute with large volumes of coarse material to the basin exceeding the subsidence rate and the basin may become overfilled. In this case, deltaic and fluvial bodies dominated by sandy and conglomeratic sandstone materials in coarsening up arrangements are developed (Blair 1987; Prosser 1993).

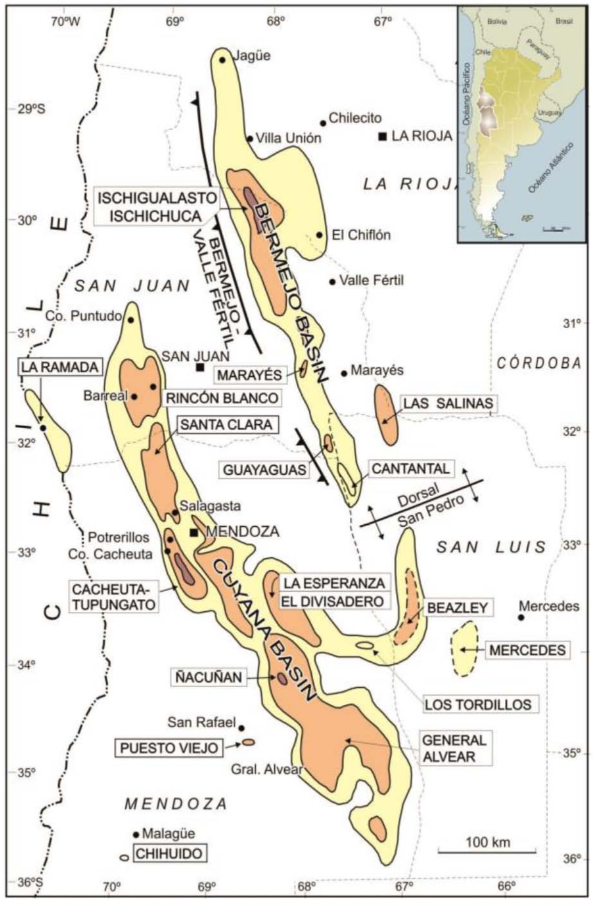

Figure 1—Triassic rift basins of central-western Argentina and their main sub-basins. From Barredo (2012)

The faults of this basin reflect the historical sequence of changing stress regime during Triassic times in the Gondwana margin (Llambías and Sato 1995; Milani and De Wit 2008; Kleiman and Japas 2009; Barredo 2012). The infilling keeps evidences of three extensional pulses derived from reactivation of the tectonic activity in the Gondwana margin (Barredo et al. 2012). Each of them is the characterized by the development of alluvial-fluvial to lacustrine facies (LAS) and lacustrine to fluvial-deltaic-fluvial facies (HAS) separated by key stratigraphic surfaces or sequence boundaries (SB). These sequences have been considered of a third order hierarchy based on biostratigraphic and isotopic dating (Barredo et al. 2012). Abundant outcrop information for most of the basin and log data for the Cacheuta Depocenter permitted to estimate higher frequency cycles induced by mostly climatic influence. These sequence stratigraphic intervals display rock properties that can be of geomechanical interest because brittle-ductile levels were differentiated and correlated among outcrops. Brittle strata tend to be enriched in quartz and/or calcite/dolomite material observed in (LAS) and ductile strata is enriched in clays and organic matter better developed in (HAS).

It is explored here these results in detail, integrating tectonostratigraphic concepts together with local scale facies analysis and petrophysics to understand the history of the Cuyana Basin continental infilling, the cyclist and the possible controls over the mechanical properties in continental sequences. The resulting data can be used to recognize best zones for horizontal drilling and artificial fracturing.

Materials and Methodology

High-resolution sedimentary logs were measured in each depocenter as part of a doctoral thesis (Barredo, 2004). Detailed studies on the geodynamics of the Cuyana Basin have been performed at the University of Buenos Aires and Instituto Tecnológico de Buenos Aires (ITBA). Hand samples were collected for sedimentological and facies analysis. Thin sections of hand samples, were studied using a petrographic microscope Nikon NI-150 SMZ 1000; Nikon Corporation, Tokyo, Japan Selected mudstones and siltstones were subjected to X-ray studies at the University of Comahue and re-interpreted at ITBA. Seismic interpretation was made with Kingdom 8.8 for academic purposes at ITBA.

Kerogen type and TOC where made at University of Buenos Aires and GEOLAB Sur (Geochemical Laboratory). Formation evaluation was performed on key wells that comprise the whole Cacheuta Formation.

Tectosedimentary setting of the Cuyana Basin

The Triassic Cuyana Basin corresponds to a passive continental rift sensu Allen and Allen (2005) developed during differential intraplate stresses derived from a backarc extension related to the Gondwanan Orogeny (Permian to the Late Triassic-Early Jurassic) and the beginning of the Mesozoic Gondwana breakup (Ramos 1992; López Gamundí 1994; Barredo 2004, Japas et al. 2008; Kleiman and Japas 2009). It reached 3700 m of predominantly alluvial, fluvial, and lacustrine clastics and subordinate carbonates interbedded with tuffs of coeval volcanism. Depocenters are NNW-SSE trending narrow asymmetric half-grabens, roughly triangular in cross section. The border fault has a stepping geometry with local change in polarity (e.g. Ramos 1992; Legarreta et al. 1993; Barredo 2004; Barredo et al. 2012). It 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 (transfer zones) (Cacheuta and Rincon Blanco depocenters) or by breached relay ramps (accommodation zones) (Rincón Blanco-Puntudo). Most of the transfers are associated with the reactivation of pre-existing zones of weaknesses in the crystalline basement and exhibits NNE-SSW direction (Barredo 2004; Japas et al. 2008). Internally, intrabasinal highs could persist throughout the synrift and postrift sedimentation along the whole basin because of its flexural cantilever origin (sensu Kusnir et al. 1991) and the resulting flexural isostatic compensation (Abarzúa et al. 2015).

Each fault segment displays greater displacement near the center, decreases to the tips and in the direction perpendicular to the center of the fault. Thus, 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 in the Rincón Blanco depocenter (Barredo 2004). The footwall of the border faults were uplifted in response to absolute upward motion coupled with the isostatic unloading. These shoulders prevented sediment inflow and streams entered the basin along the hinged margin and axially, mostly sourced by the transfers. The rift was not connected with the sea and 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 and the textural characteristics of the lithological bodies.

Field studies and seismostratigraphic analysis show that fault reactivation events were common during the quasistatic event on the western margin of Gondwana during Middle to Late Triassic (Barredo 2012). These recurrent extensional pulses were named Rift I, II and III and their corresponding synrift deposits by Barredo (2004) and Barredo et al. (2012) and controlled the extension along the Cuyana Basin and impinged several different characteristics to the infilling of the Cerro Puntudo (CPD), Rincón Blanco (RBD) and Cacheuta (CD) depocenters (Fig. 1). These pulses are clear from the switch between major fluvial and lacustrine environments, growth structures and well developed allosurfaces along the basin. 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 (Barredo et al. 2012). During Rift I, the deposits were restricted to a series of partially isolated depressions and filled with LAS consisting of alluvial-fluvial coarse clastic facies (Cerro Puntudo (CPD), Ciénaga Redonda (RBD) and Río Mendoza (CD) formations). They are covered by HAS of interfingering fluvial, sandstones and tuffs and lacustrine/playa-lake settings (Cerro Amarillo (RBD) and Cerro de Las Cabras (CD) formations) (e.g. Kokogian et al. 1993; Spalletti 2001; Barredo 2004). This first sequence is separated by a regional unconformity by the second depositional phase or Synrift II. It starts with LAS of fining-upward sequence of sandstones, black shales and tuffs, all related to braided to high sinuosity-river systems (El Relincho (PD), Panul, Casa de Piedra (RBD) and Potrerillos (CD) formations) which grade into a widespread lacustrine setting with the development of HAS (Carrizalito, Monina (RBD) and Cacheuta (CD) formations). Finally, this second rifting stage passes upward to shallow lacustrine to fluvial-deltaic sandstones, shales, and tuffs of the top of the HAS deposited during the early to late post-rift (Upper Carrizalito (RBD) and Cacheuta (CD) formations). The Synrift III marks a new regional reactivation in fault activity and is represented by an alluvial-fluvial succession but no important lacustrine bodies have been found yet, the infilling is represented by Marachemill and Cepeda formations in RBD (Barredo 2004; Abarzúa 2016).

The 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. This contractional regime gave place to inverted sub-basins characterized by normal faults with reactivated inverse displacement, new inverse faults, and fault propagation folds.

Geology of the lacustrine facies and their tecto-climatic controls

During Rift I, lacustrine facies were represented by Cerro Puntudo, Cerro de las Cabras and Cerro Amarillo formations. This latter was developed on the RBD close to the border fault reaching 600 m thick. The Cerro Puntudo lake developed on the ramp of the CPD and reaches 75 m thick (Mancuso et al. 2010, Abarzúa 2016), while Cerro de las Cabras developed in de CD close to the transfer zone and reaches 900 m thick. Both are calcareous-rich alkaline playa lake bodies with import subaerial exposures. They are composed of well-stratified gray limestones, stromatolitic limestones, reddish brown mudstones, colorful fine-grained sandstones, tuffaceous mudstones and green tuffs. Marginal facies comprise mudflats built by ephemeral sheetflows and palustrine limestones with primary and reworked fall ash deposits. Reddish brown tabular siltstones interfingered with mudstones compose the mudflats. Siltstones display erosive bases internally can be laminated or ripple-cross laminated with wave ripples and convolute structures. Mudstones are horizontally laminated with alternating 2 mm thick fine yellowish sandstone (with low-angle ripple cross-lamination) and 1 mm thick mudstone. It finishes with a massive fabric. Both lithologies show mud drapes, mudcracks, mud chips and pedogenic levels interpreted as probably vertisols fed by underground waters (Barredo 2004; Benavente 2014). Soils are mottled with system of vertical and horizontal cracks and root traces 3 mm in diameter are common, they are filled with calcite and probable silica coating and organic matter. Micritic intraclasts with ostracods are present, they reach 1 cm long and are rounded. Thin calcite crusts are also present. Main mineralogy for mudflat comprises lithic limestone fragments, oncolites, angular quartz, feldspar, biotite, less than 20 % clays. Conversely soils hold abundant (>60%) smectites that sometimes make aggregates of sand-size because of their expandable behavior. There are also analcime-rich illites derived from diagenesis of the abundant alkaline volcanic rocks. This mineralogy points to alkaline–saline waters (Renaut 1993; Cabaleri et al. 2013) subjected to a semi-arid and seasonally more humid climate. Palustrine environments comprise carbonate mudstones, limestones represented by wackestones and mudstones with domic lamination (stromatolites). Sequence is green, biogenic and display occasionally subaerial exposures with pedogenic levels. Wackestones (up to 4 m thick) contain nodules can reach 2 cm in diameter and randomly distributed clay clasts. Cracks are vertical and horizontal and filled with calcite and lined with clay. Mudstones (up to 2 m thick) are grey, micritic, with horizontal and thin (less 1 mm thick) laminae of organic matter. It is also common the occurrence of mud chips, peloids, anhydrite lenses and spherulites. Freshwater cyanobacteria, charophytes and ostracodes have been reported by Benavente (2014). The outer portion of this environment was subjected to subaerial exposure with soils development represented by mottling, cracks, root traces and tubules of 1mm in diameter. Clays in this case reach 40-60%. Cracks are vertical and horizontal and filled with calcite and lined with clay, root tubules are filled with spar calcite. The off shore lake facies comprise stromatolitic limestones massive (up to 2 m thick) to laminated mudstones (up to 4 m thick) and marlstones (20 cm thick). These latter are reddish grey and composed of alternating laminated sandstone and clay of 1mm (smectite and illite). Lenticular 10 to 70 cm thick oolitic grainstones and oncolitic floatstones have been reported by Benavente (2014). Mineralogy of these facies is similar to that of the mudflat, grains of quartz, biotite, hematite, feldspar and lithic fragments (10%), and abundant carbonate grains. Microspar, spar, microgranular quartz and chalcedony are randomly distributed within the micritic texture. Cerro Puntudo and Cerro de las Cabras formations contain mostly amorphous kerogen II that can reach 10% in the latter (Legarreta and Villar 2011, Barredo and Stinco 2013).

Cerro Puntudo lake facies are arranged in mostly aggradational and less progradational stacking pattern that points to a fluctuating profoundal facies evolution diagnostic of a balanced-fill lake type (sensu Bohacs et al. 2000). Cerro de las Cabras on the other hand, is dominantly aggradational indicative of an underfilled playa lake (sensu Bohacs et al. 2000). Lakes were fed by surficial and underground water in semiarid climate with humid seasonality (Barredo and Stinco 2013). Block rotated highs gave place to a marked topography with strong local conditions and probably rain shadow. Thin calcite interlayered crusts may be indicative of strong evaporation (Hardie et al. 1978) of the border lake but vertic soils with smectites and well-developed vegetation cover including herbaceous hygrophytes and sphenophytes (Mancuso 2009) suggest some humidity, it was a humid playa –lake (sensu Liutkus and Wright 2008). Both were hydrologically open lakes (probably in the subsurface) developed during LAS to relative HAS with a similar rate of accommodation space and water + sediment supply. Being hydrologically open lakes, the accumulation of thick evaporites was not possible (Rosen 1994). Paleosoils imply long time exposure when subsidence surpasses water + sediment supply (Alonso-Zarza et al. 2012) suggesting activity in the faults while hydrological fluctuations were probably related to climate variations through time, sometimes amplified by tectonic activity. Groundwater table level fluctuations may have caused pedogenesis and subaerial exposure of the deposits.

The Cerro Amarillo lake (RBD) reaches almost 600 meters. It corresponds to a shallow, mostly ephemeral lacustrine environment associated with distal fans and bajadas. Marginal facies comprises sandflats compose of sandstones/siltstones arranged in sheet like stacked amalgamated layers of less than one meter thick. Individual beds range from several cm thick up to 1 m, are massive or display horizontal to low angle stratification, and small-scale trough cross-stratification. They are mostly normally graded being capped by ripple cross-laminated sandstones and a thin drape of mudstones with raindrops and deep vertical cracks filled with spar calcite and lined by green silts. These latter features and the existence of swelling clays (>30%) suggest they correspond to vertic paleosoils. At top of these facies, there are brecciated carbonate horizons with floating quartz grains, and karst features. Mineralogy comprises quartz, k feldspar, oligoclase, sanidine, muscovite and analcime, lithics and carbonate cement (calcite and dolomite) and scarce hematite anhydrite lenses alternating. Palustrine environments contain well drained calcimorphic soils with tubular root systems surrounded by calcareous nodules and concretions. Clays (~50%) include chlorite, interstratified illite/smectite (montmorillonite). The off-shore lake facies comprise (1-1,5 m thick) heterolithic mudstones with isolated horizons of current-rippled sandstones, load casts and flame structures are common at the interface between sandstones and mudstones. Carbonatic, dark brown and gray massive to parallel laminated organic mudstones and marlstones that can reach 2 m thick sometimes display alternating decimeter – bedded, fine sharp based and laminated silts and anhydrate lenses. At a microscopic scale massive organic levels are horizontally and wavy laminated with bad preserved palynomorph and isolated pyrite crystals. The present 5% COT HI 950 mg HC/g with of I/II kerogen type (Barredo 2004). Mineralogy corresponds to quartz, feldspar, calcite+dolomite (< 30%), clays like smectite and illite. Near the top of the formation, the sequence is characterized by pebbly mudstones with scarce organic matter (1% TOC) which pass into a series of thickening and coarsening upward units corresponding to thin sandstone beds and finally amalgamated sandstones of 1 m thick of the top of the HAS in the early post-rift.

The Cerro Amarillo lake displays a mostly aggradational stacking pattern indicative of an underfilled playa lake (sensu Bohacs et al. 2000), like Cerro de las Cabras Formation, developed in the deeper portion of the through close to the border fault. It was a shallow alkaline body associated with mudflats and palustrine environments (Barredo 2004). Lake was fed by surficial and underground waters in semiarid climate with humid seasonality (Barredo and Stinco 2013). The existence anhydrite lenses point to semiarid climate (Hardie et al. 1978; Wright 1986) but ferric smecties (nontronite) of the top of the lake suggest more tempered and wetter conditions. Numerous subaerial exposures suggest strong wet-dry cycles induced by climatic local variations.

Rift II was developed under wetter conditions than Rift I. High accommodation sequences (HA) of lakes are represented by Carrizalito-Monina formations (RBD) and Cacheuta Formation (CD). There are no lacustrine outcrops associated with El Relincho Formation in the Cerro Puntudo Depocenter (CPD).

The Carrizalito Formation reaches 250 meters. It is composed of a thick alternating shallowing and deepening lacustrine cycles in the base (Borrelo and Cuerda 1965; Barredo 2004). Each cycle (0.6–1.0 m thickness) is characterized by massive and bioturbated fine, rippled (wave and current) sandstones, greenish-grey wavy laminated siltstones and mudstones which alternate with light-brown marls, tuffaceous sands ash-fall tuffs. They suggest shallow standing waters with important wave reworking. Subaerial exposures of the lake margin are represented by clayey mudstones with desiccation cracks, synaeresis cracks, raindrops and trace fossils (Barredo 2004). Mineralogy corresponds to abundant quartz, feldspar, and calcite. Clay reaches (20-25%). Tuff composed of pumice detritus, quartz k-feldspar and carbonatic cement. These sequences are laterally and vertically interfingered with thinly stratified silty sandstones and massive mudstones. They are heterolithically interbedded with carbonate mudstones. Calcite is the main mineral with scatter dolomite and quartz. Occasionally, they are associated with massive or horizontally laminated marls (30 cm in thickness) and pale-grey thin (< 1 cm thick) organic levels (plant debris) which consist of laminated shales with micritic calcite. Marls comprise mainly dolomite, magnesium calcite, quartz, and clays: interstratified illite/smectite/montmorillonite calcic, kaolinite. The deep-lake deposits are composed of dark gray, thinly laminated and massive bituminous shales with macro pyrite crystals along bedding plane and chert nodules. Mineralogy is represented by quartz, chert, K-feldspar, plagioclase goethite and limonite, pyrite, clays (sericite, chlorite and interstratified illite/smectite (calcic montmorillonite), biotite, analcime and magnesium calcite, (aragonite?) Alternating rhythmic lime to clay couplets are common with isolated dropstones pushed by floating plants. TOC reaches 7-8% to 10% and HI is 700mg HC/g. It is composed of amorphous, kerogen type I/II (Citrinovitz et al. 1975; Barredo 2004). 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 thick deltaic deposits with abundant ash-fall tuffs and chonites frequently indurated with siliceous replacement. They were developed in the early-postrift stage.

To the flexural margin deep lacustrine facies and fluvio-deltaic facies are represented by the (Monina Formation) (Baraldo and Guerstein 1984; Barredo et al. 2015). Facies are almost the same as Carrizalito Formation but marginal to coastal environments display more carbonatic facies and include sandstones, marls with algae lamination, thin laminar stromatolites, wackestones, oolitc and bioclastic grainstones (Barredo 2012). Deep lacustrine bituminous shales are organic-rich rhythmic laminites with a kerogen type I mostly algal and scarce type II with TOC values between 9 to 14% and HI values around 650-700 mg/g/COT (Citrinovitz et al. 1975, Barredo 2004; Zamora Valcarce et al. 2009).

The lacustrine facies of the Carrizalito Formation (RB) corresponds to a balanced lake (sensu Carroll and Bohacs 2001), developed close to the border fault that evolves to an overfilled lake during the early post-rift (Barredo 2012). It is estimated that it was rather deep, fresh to mildly characterize by repeated cycles of shallowing-deepening couplets of progradational/aggradational shoreline stacking patterns the evolved to a well-developed progradational stacking pattern sequence during the upper HA stage in the early-post-rift. The Monina lake instead, seems to have evolved as a balanced fill lake dominated by shoaling levels with progradational stacking pattern.

The Cacheuta Formation ranges from 50 to 400 meters. It is characterized by massive and thinly laminated and tabular mudstones, tuffs, tuffaceous siltstones and volcaniclastics, mostly chonitic, levels, limestones and fine sandstones (Fig. 2). The base and top of the sequence are composed of fluvial–deltaic deposits (1-5 m thick) of trough-cross bedded lenticular sandstones interbedded with laminated mudstones with diverse with well-preserved algae association characteristic of oxygen-rich freshwater environments. They vertically and laterally interfinger with marginal facies composed of fine, horizontal to ripple-laminated sandstones, thinly stratified silty-sandstones to siltstones, with conchostracans, fish, plants debris and massive mudstones. Deep lacustrine facies comprises, massive mudstones, tuffaceous mudstones and massive to horizontally laminated carbonaceous claystones (1 cm to 5 cm). Mineralogy comprises quartz, K-feldspar, biotite, goethite and limonite, pyrite, clays (chlorite and interstratified illite/smectite (montmorillonite), analcime and aragonite. They are bituminous shales that contain total organic carbon (TOC) content of 3 to 10%, Romax (%) 0.6 to 1, Hydrogen Index 600-900 mg HC/gTOC and made up of type kerogen I, and a VKA of algae dominate Botryococcus, palynomorphs in association with amorphous kerogen with limited terrestrial contribution "Ipswich-type" microflora (Zavattieri et al. 1996, 2007; Legarreta and Villar 2011). According to Mello et al. (1997), oils composition varies from waxy to very waxy (saturates > 70%), have sulphur contents < 0.08 % and prystane/phytane ratios > 2. To the top coarsening-upwards parasequences interpreted as mouth bar deposits in river-dominated deltas with evidence of progradation are associated with the transition to the post –rift.

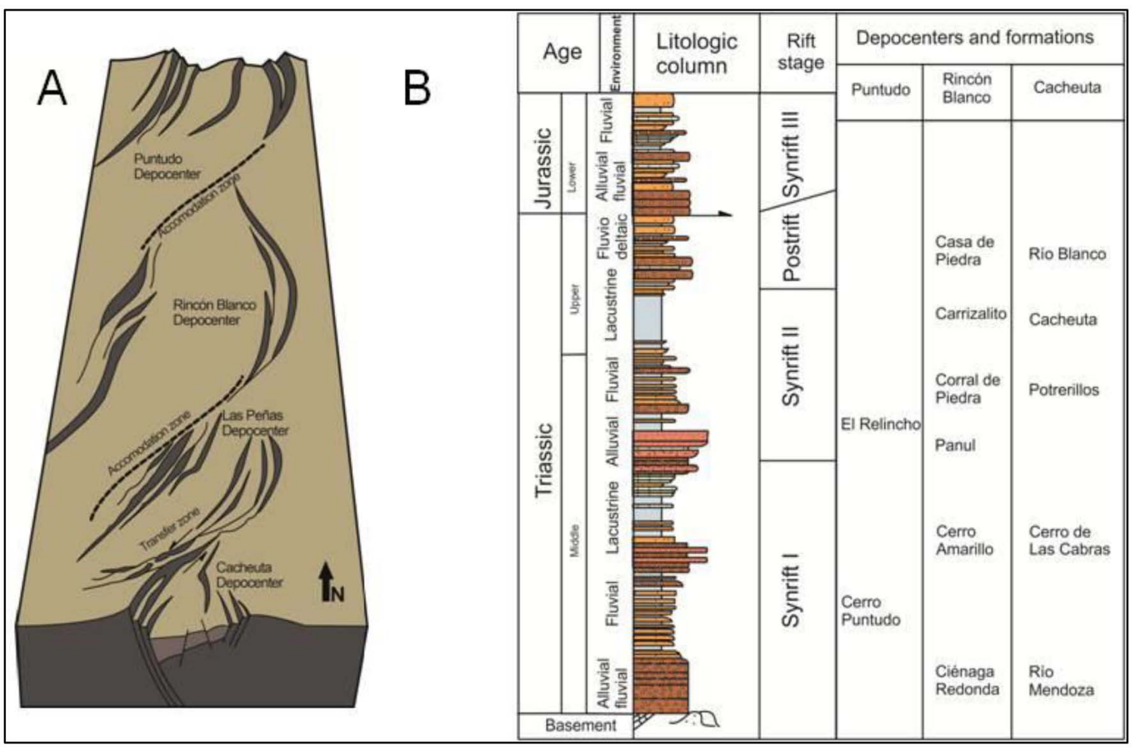

Figure 2—A: Cuyana Basin main depocenters. Border faults (BF) have a stepping geometry and opposite dip directions (Cacheuta and Santa Clara-Rincón Blanco) or keep the same dip orientation as between Santa Clara, Rincón Blanco and Puntudo depocenters. Major segments are related through accommodations zones which constitute intrabasinal highs. B: general stratigraphic column, rift stages and their corresponding sedimentary environments. To the right, studied depocenters and their formational units. Modified from (Barredo 2012).

The Cacheuta Formation represents the infilling of an overfilled lake (sensu Carroll and Bohacs 1999). It was a rather deep, stratified and hydrologically open lake (Spalletti 2001) (Fig. 3). Bottom was quiet but some climatic induced water mixing was observed with silty claystones and fine turbiditic sandstones and broken tiny fossils. The fossil record points to a highly seasonal, sub-tropical (Barredo and Stinco 2013) probable warm-temperate (Zavattieri et al. 2007).

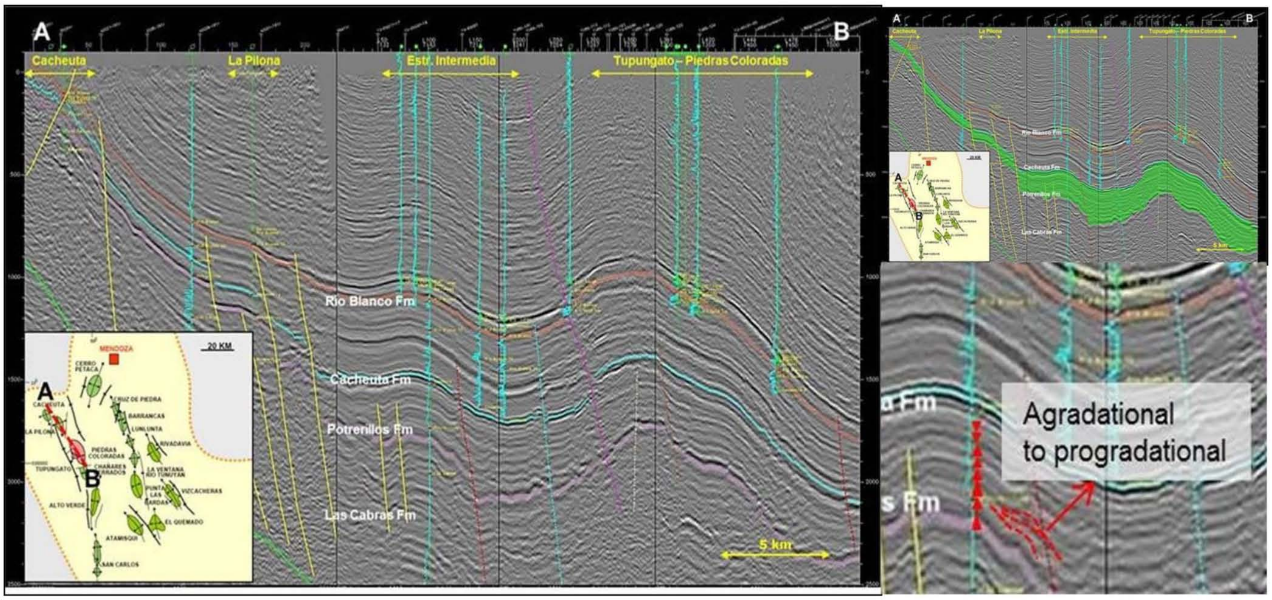

Figure 3—Left, seismic line of Tupungato depocenter and the corresponding formational units. Upper right shows the Cacheuta Formation thickening towards the Tupungato depocenter. The seismic line crosses many oil fields that have been producing hydrocarbons from different reservoirs within Río Blanco Formation, genetically related to the rich oil shales of the Cacheuta Formation. Lower right, within the unit, some reflections can be observed and were interpreted as shallowing-deepening cycles of the lake. Cycles (red triangles) are clear at the base of the unit and their arrangement point to an aggradational to progradational stacking pattern (dot lines).

Discussion

Continental shales are laterally and vertically heterogeneous because of the numerous synsedimentary allogenic controls that take place during basin evolution. Lake complexity is associated with its morphology, extent and deepness which, at the same time, are associated with the irregular topography of the rift basin. Additionally, lakes are quite sensitive to climate, water input (surface or underground), and their associated bioproductivity which induce high frequency cyclist with the resulting increment in mineral and textural heterogeneity.

In this sense, balanced fill and underfilled lakes undergo repetitive contraction an expansion of the water body which leaves behind a series of features that might influence the mechanical rock behavior. They result from the balance between tectonics and sediment+water input creating and destroying space for sedimentation. According to the models presented herein for the Cuyana Basin, sandstones, shales and carbonates of shallow lakes are deposited during low accommodation basin space (LAS) while thick shales/ carbonates and source rocks are deposited during periods of rifting climax when high accommodation space (HAS) permit long-term base level highstands of the lakes. Mixed sandstones and shales in upward coarsening sequences dominate the early post-rift stage when basin expands but subsidence begins to decrease through time. Because the Cuyana Basin rift underwent repetitive reactivations of the extensional system, three third order sequences were interpreted and identified as Synrift I, II and III.

These Triassic lakes were variable mixed silicoclastic–carbonatic with numerous forth to fifth order climatic induced cycles with minor tectonic components. During Rift (I) mostly underfilled playa-lake environment dominated the landscape. Sequences of fourth order were aggradationally stacked with minor retrogradational tendency in the balanced-fill Puntudo lake (CPD) but aggradational in the Cerro de Las Cabras and Amarillo underfilled lakes. Marginal and deep facies of these environments contain different amounts of clays, minerals that give plasticity to the rock. This mechanical property is due to their laminar morphology, high surface area and high swelling capacity. Water in clays is present in three forms: chemically hydration; surrounding the mineral particles or as interstitial, filling the voids between the grains. The plasticity of clays is related to the morphology of the plate-like clay mineral particles that slide over the others when water is added, which acts as a lubricant. As the water content of clay is increased, plasticity increases up to a maximum. Plasticity is also referred to as "extrudability", "ductility", "workability" or "consistency" (Händle 2007).

Table 1—Tectono-sedimentary synthesis of the Cuyana Basin infilling. Facies and mineralogy according to the mechanical characteristics. For details see text. SR (synrift). LAS-HAS (low-high accommodation space). S: sandstone, Md: mudstone, Bsh (bituminous shale, Mr: marl, CMd: calcareous mudstone; Slt: siltstone, Tf: tuff, C: carbonates, Wck: wackestone. OM: Organic Matter. Bi: biotite, Ca: calcite, Cly: clay, Dol: dolomite, F: feldspar, ill: ilmenite, Kao: kaolinite, Mv: muscovite, Mon: montmorillonite, Ol: oligoclase, Ox: oxides, Pl: plagioclase, Py: pyrite, Q: quartz, Se: sericite, Sm: smectites, Sn: sanidine, Yh: gypsum lenses

Depocenter	Rift	A/S	Fm	Stacking Pattern	Environment	Facies	Texture	Mineral - Fossils	Mechanical strata
Cerro Puntudo (CPD)	SR I	LAS	Cerro Puntudo	Aggradational Rather progradational	Alluvial-fluvial				
					Balanced fill: Shallow playa-lake Mudflat	S/Slt/Md	Lamination Ripple-cross lamination Massive	Qz,F,Bi,Ca, Cly(<20%) sm,ill,an	Brittle
						Soil	Massive Vertical cracks, tubules Intraclast	Qz,F,Bi,Ca, Cly(>60%) sm,cl,ill-sm Ostracods	Ductile
		HAS			Palustrine	Wck-Cmd	Lamination Stromatolites	Cl, Dol, Qz,Bi Cly(20%) sm,ill	Brittle
						Soil	Mud chips, spherulites Cracks (V+H) Yh lenses	Cl, Dol, Qz,F Cly(40-60%): cl,ill/sm(mont)	Ductile
					Playa lake	C-Md	Lamination (Hz+wvy) Stromatolites Hetherolitic	Qz, F,Ca+dol,Bi Cly(25%): sm,ill	Brittle
					Off-shore	C/Mr/Md	Lamination Massive	Qz, F,Ca+dol, OM Cly(40%): sm,ill	Ductile
Rincón Blanco (RBD)	SR I	LAS	Ciénaga Redonda	Aggradational	Alluvial-fluvial				
					Underfilled: Shallow playa-lake Sandflat	S,Sil,Md	Lamination Low angle strat. Trough cross-strat Ripples	Qz, k-F,Pl,Sn,Mv,ca+dol Ox,Yh Cly(< 30%): cl, ill/sm(mont)	Brittle
			Cerro Amarillo			Soil	Lamination Vertical cracks Root tubules Concretions	Qz, k-F,Pl,Sn,ca+dol Ox,Yh Cly(> 30%): cl,ill/sm(mont)	Ductile
		HAS			Palustrine	Wck-Cmd	Lamination Stromatolites	Cl, Dol, Qz,Bi Cly(20%) sm,ill, Kao.	Ductile
						Soil	Mud chips, spherulites Cracks (V+H) Yh lenses	Cl, Dol, Qz, Cly(> 50%):cl,ill/sm(camont)	Ductile
					Playa-lake	C-Md	Lamination (Hz-wvy) Ripples Hetherolitic	Qz, F,(< 30%) Ca+dol, py,Yh, Bi	Brittle
					Off-shore	C/Mr/Md	Lamination Massive	Qz, F,(>30%Ca+dol),py,OM	Ductile
	SR II	LAS	Panul Corral de Piedra	Aggradational	Fluvial				
					Balanced fill: Shallow lake	S/Md/Mr/ Tf	Lamination Subaereal cracks Stromatolites	Qz, KF,bi,Ca,Ox Cly (20-25%): ill/sm,an, Conchostracans, plants	Brittle
			Carrizalito Monina			Wck,Gr,Mr, (Rmp)	Ripples Wavy lam.	Cly (18%): ill/sm,an, Conchostracans, plants	Brittle
		HAS			Distal	Slt/Md/CMd /Mr	Lamination Heterolithic Wavy lam.	Qz,K F,Ca+dol,OM Cly (>40%); ill/sm, mont,ka Plant debris	Dc to Br
					Lacustrine Off-shore (deep)	Md(Bsh),Mr, CMd	Lamination Micro Wavy lam.	Qz,chertmK-F,Pl,Ox,Py, ca,OM Cly (>40%); se,cl,ill/sm, ca-mont,an	Ductile
Cacheuta (CD)	SR I	LAS	Río Mendoza	Aggradational	Alluvial-fluvial				
		HAS	Cerro de Las Cabras		Underfilled: Shallow playa-lake Mudflat	S/Slt/Md	Lamination Ripple-cross lamination Massive	Qz, F,Ca+dol,py,Mv Plant debris	Brittle
						Soil	Massive Cracks (V-H), tubules Intraclast	Qz,F,Bi,Ca, Cly(<60%) sm,cl,ill-sm Ostracods	Ductile
					Palustrine	Wck-Cmd-Md	Lamination Hz-wvy Stromatolites	Cl, Dol, Qz,Bi Cly(25%) sm,ill,Kao	Brittle
						Soil	Mud chips, Yh lenses Cracks (V+H)	Cl, Dol, Qz,F Cly(> 45%): cl,ill/sm(mont)	Ductile
					Playa-lake	C-Md	Lamination Stromatolites Hetherolitic	Qz, F,Ca+dol,Bi Cly(20%): sm,ill	Brittle
					Off-shore	C/Mr/Md	Lamination Massive Micro wavy lam.	Qz, F,Ca+dol, Py Cly(>40%): sm,ill	Ductile
	SR II	LAS	Potrerillos	Aggradational Prograddational	Fluvial				
			Cacheuta		Overfilled (Rather balanced): Shallow lake	Tf,Slt/Md/C/S	Lamination (H-Rp) Hetherolithic Subaereal cracks Ripples	Qz, F,bi,Ca,Ox Cly (20%): ill/sm,an, Conchostracans, fish, plants	Brittle
		HAS				Md/TfMd,CMd	Lamination Heterolithic Wavy lam.	Qz, K-F,bi,Ca,Ox,py,OM Cly (35%): cl,ill/sm,an,	Dc to Br
					Distal	Slt/Md/CMd /Mr	Lamination Heterolithic Wavy lam. Massive	Qz,K F,Ca+dol,OM Cly (>45%); ill/sm, Ca-mont, ka Plant debris	Ductile
					Lacustrine Off-shore (deep)	Md(Bsh),Mr, CMd	Lamination Micro Wavy lam.	Qz,chertmK-F,Pl,Ox,Py, ca,OM Cly (40-100%): cl,ill/sm,an,	Ductile

Marginal facies of all of them includes mudflats/sandflats and palustrine environments (Table 1). Mudflats comprise couplets of siltstone-mudstones and soils. Siltstone-mudstones are laminar to massive and include dominant quartz as siliciclastic grains and cement, feldspar, biotite. Calcite is present as cement and even as thin crust between layers. Clay fraction (<20%) is represented by smectites, illite and analcime with moderate plasticity index (sensu Atterberg limits in Bain, 1971). On the basis of Jarvie et al. (2007), Wang and Gale's (2009) and Garcia et al. (2013) models less than 20 % means that the influence of these clays are pretty low and so material will be brittle for hydraulic stimulation. Non representative organic matter has been found and clay content is below 30%. However, these same levels were subjected to pedogenesis in numerous sectors of the basin. In this case, lithofacies ends with massive levels with similar mineralogical composition but clay amount increases up to 60-80 % and is mostly represented by expandable smectite, but chlorite, interstratified illite/smectite (ca montmorillonite) are also present.

According to their rheological properties (sensu Atterberg limits, in Bain 1971) and it high parentage they make the material ductile for hydraulic stimulation (Table 1). In terms of textural heterogeneity, brittle levels are composed of interfingering siltstone-mudstones which are internally laminated, with occasional low-angle ripple cross-lamination. Sometimes there are thin calcite crusts along contacts. These characteristics represent differences in elastic properties between layers and can themselves be natural fractures because they are surfaces of stress concentration where failure will preferentially occur (Davey 2012). However internal lamination could act as barriers to fracture growth as energy is lost along the lamination surface (McCounaughy and Engelder 1999). Soils are abundant in the sequence and comprise mainly vertical cracks and root tubules of 3 mm in diameter, filled with calcite and probable silica coating and organic matter. Micritic intraclasts with ostracods are present. These characteristics make these levels horizontally heterogeneous for fault propagation and sure will have implications for hydraulic stimulation and completion design. Palustrine facies are much more biogenic and carbonatic. They are composed of limestones (wackestone-mudstones), and carbonatic mudstones. The composition is mainly calcite, dolomite, quartz (micro grains and patches of chalcedony), and biotite, with 20 % of clays which points to a brittle behavior (Table 1). On the other hand soils observed present > 40% of clays (chlorite, interstratified illite/smectite (montmorillonite)) that make them rather ductile.

Textural characteristics is dominated by lamination, which gives this facies a vertical anisotropy but the existence of lateral discontinuous stromatolites, mud chips, peloids, anhydrite lenses and spherulites adds a horizontal heterogeneity that should be considered. Soils present the same textural fabric as mudflats. Being this lakes exposed to long subaerial climatic induced exposition these numerous barely to well developed soils are arranged in climatic fourth to fifth order packages; a maximum of twenty five cycles of fourth order were observed for Cerro de las Cabras and Cerro Amarillo formations and 16 cycles for Cerro Puntudo Formation. Soils are dominated by clays and thus are more ductile permitting to approximate a mechanical cyclicity for these sub-environments (Fig. 4).

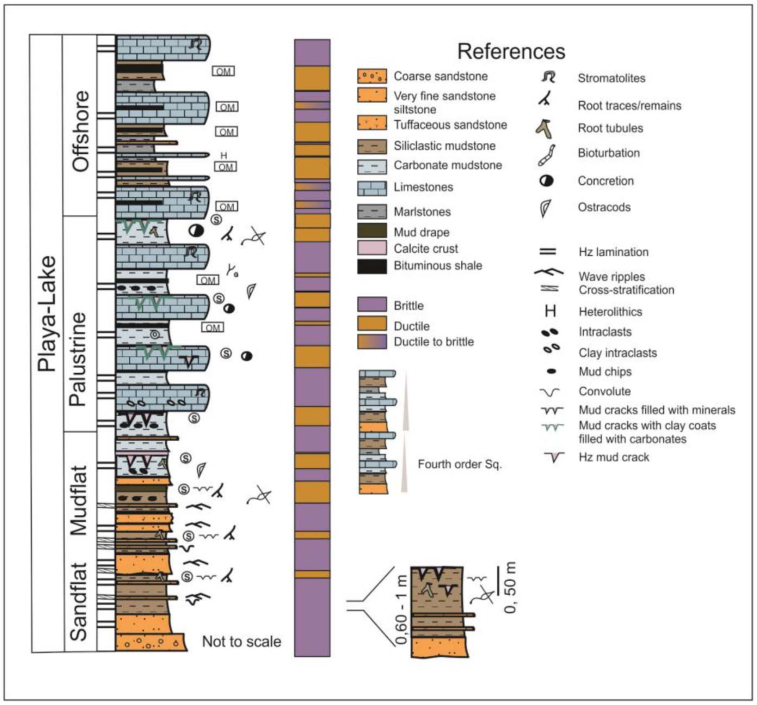

Figure 4—representative fourth order sequence for the playa lakes with their corresponding environments (Cerro Puntudo, Cerro Amarillo and Cerro de Las Cabras formations). To the right, packages of brittle-ductile strata based upon mineralogy and organic content. Mechanical cycles are associated with subaerial exposure and soil development of the marginal facies and mainly with the presence of organic matter in the high stand lake facies. OM (organic matter), S (soil). Textural anisotropies are determined by the sedimentary structures and some biogenic fabric, see text for details.

Deeper facies are composed of stromatolitic limestones, massive (up to 2 m thick) to laminated mudstones (up to 4 m thick) with OM, heterolithic mudstones (1-1,5 thickness) and marlstones (20 cm thick). Stromatolitic limestones and heterolithic mudstones are brittle. Their composition is quartz, feldspar, calcite +dolomite, clays like smectite and illite total 25%. Marlstones are composed of alternating, laminated siltstone and 40% clay of 1mm (smectite and illite) which makes them ductile. The Cerro de Las Cabras and Cerro Amarillo lake bodies display carbonate minerals (magnesium calcite+dolomite), pyrite crystals, organic matter (5% to 10%) that makes of the mudstones ductile levels. However in certain points of the basin, much close to border faults there are more carbonates reaching up to 30 % that suggest they can be rather brittle. Textural characteristics show that all these facies are strongly laminated. Mudstones at microscope show they are horizontally and wavy laminated so they are vertically anisotropic. In the case of these deeper facies, ductility is associated with the presence of organic matter which, in terms of bioproductivity and preservation, correspond to a permanent water body developed during a more humid period with long lasted humid alternating seasons.

During Rift II stage, lakes were deeper, stratified and corresponded to balanced fill and overfilled types. Sequences of fourth order were aggradationally stacked in the balanced-fill of Carrizalito-Monina lakes (RBD) but aggradational and progradational in the Cacheuta lake (CD).

Carrizalito-Monina lakes are cyclic with cycle of 0.6–1.0 m in thickness. Marginal facies are composed of massive and bioturbated fine, rippled (wave and current) sandstones, wavy laminated siltstones and mudstones which alternate with marls, tuffaceous sands ash-fall tuffs. More carbonatic facies of the ramp system of the rift include marls with algae lamination, thin laminar stromatolites, wackestones, and oolitc and bioclastic grainstones. Organic matter is constrained to coal seams of 1-2 cm thick. Mineralogical composition corresponds to quartz, feldspar, calcite and 17% of clays (illite/smectite). Tuffs are composed of pumice detritus, quartz k-feldspar, and abundant carbonatic cement. These levels can be considered brittle for hydraulic fracturing (Fig. 5). Textural characteristics point to lamination as main vertical heterogeneity but the existence of desiccation cracks, synaeresis cracks, and abundant trace fossils add some horizontal fabric variability that has to be considered.

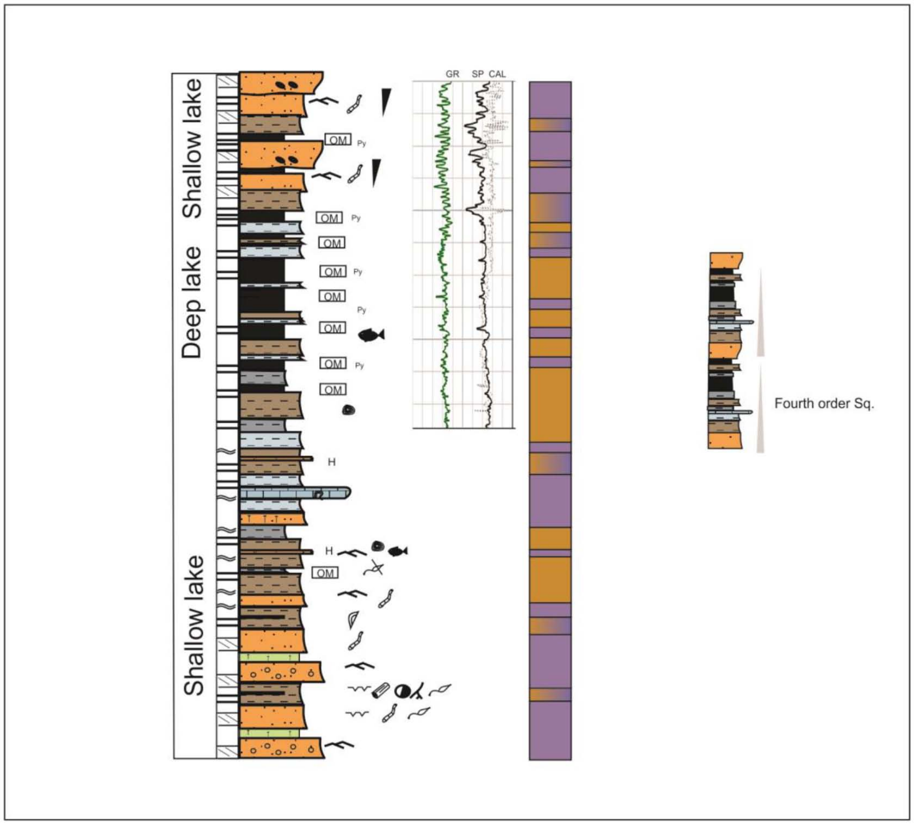

Figure 5—representative not to scale fourth order sequence for the perennial lakes with their corresponding environments (Carrizalito/Monina and Cacheuta formations). Brittle-ductile levels were based upon mineralogy and fossil content and are related with deepening and shallowing of the lakes. This is most clear in the Carrizalito Formation which is a balanced fill lake however Cacheuta Formation seemed to have behaved more like an overfilled lake with less developed cycles. In spite of this latter, log data from Tupungato depocenter matches quite well with observed surface cycles permitting to assign a general mechanical stratigraphy to the sequence. See figure 4 for references. Textural anisotropies are determined by the sedimentary structures and some biogenic fabric especially in the shallow marginal facies.

More distally to the coast thinly stratified silty sandstones are interlayered with carbonate mudstones in a hetherolitic arrangement. They are associated with marls (30 cm in thickness) composed of mainly dolomite, magnesium calcite quartz, 45% of clays interstratified illite/smectite/calcic montmorillonite and, kaolinite. There are also organic levels (plant debris) (1% of COT) which consist of laminated shales with micritic calcite. These packages are quite heterogeneous but can be considered ductile to rather-brittle because of the presence of low plasticity kaolinites. Textural characteristics show important lamination as the main vertical heterogeneity. Deep lake facies are composed of massive and thinly laminated bituminous shales with macro pyrite crystals along bedding plane and chert nodules. Total organic matter ranges (3-14%). There are also beds of alternating lime to clay couplets. Mineralogy is represented by quartz, chert, K-feldspar, plagioclase goethite and limonite, pyrite, (40%) clays (sericite, chlorite and interstratified illite/smectite (calcic-montmorillonite), biotite, analcime and magnesium calcite, (aragonite?). These facies are ductile for fracturing being the most important textural anisotropy the strong lamination of the deposits (Fig. 5).

The Cacheuta lake is similar but cyclicity is not so marked and characteristic compared to the northern Carrizalito-Monina lakes. In subsurface, the variable clay/silt/lime/organic matter composition can be recognized through logs and laboratory data (Fig. 6). Information from one well located within the Tupungato depocenter shows well defined vertical heterogeneities that can be interpreted from the Gamma

Ray and resistivity logs. Poisson´s ratio and Young´s modulus were estimated from logs together with a brittleness average (sensu Grieser and Bray 2007). For this particular case, mostly deep facies has been penetrated by the log. They are rich in OM (3 to 10%) and are ductile with thin less ductile to rather brittle levels associated with rhythmic facies. The more fragile intervals match with the relatively low total organic carbon content and can also be observed that coincides were the caliper shows more rugosity with abundant cavities. These characteristics are mostly present in the upper zone of the Cacheuta Formation and correspond to the marginal facies. The good correlation among forth order sequences from surface and from subsurface data (Figs. 5 and 6) permitted to propose a good mechanical cyclicity for this unit.

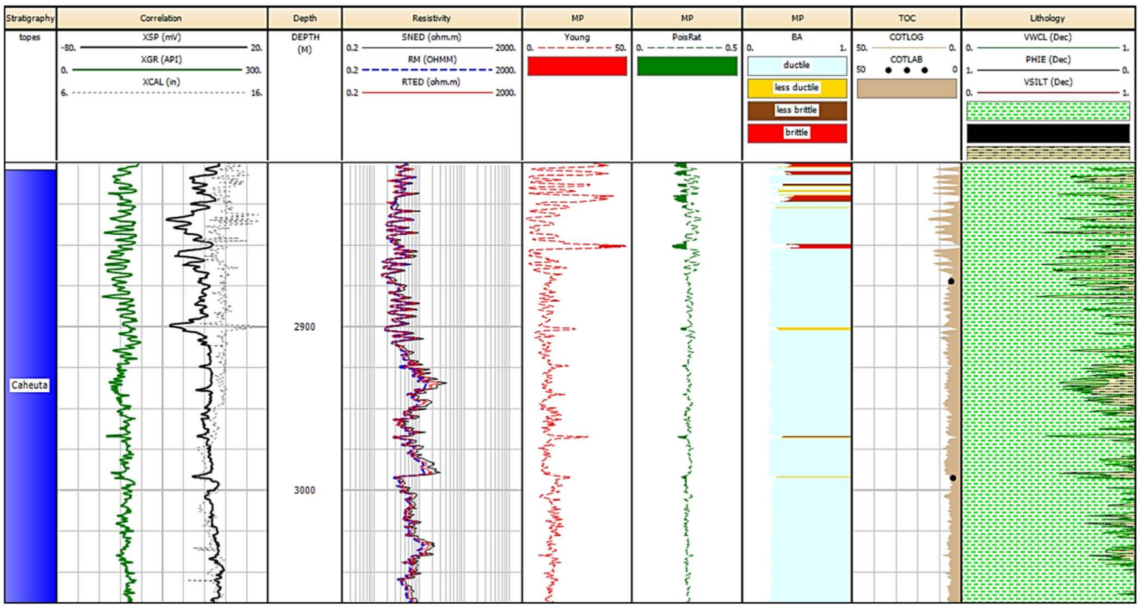

Figure 6—Formation evaluation on a well located in the Tupungato depocenter. Tracks #1: stratigraphy; #2: Spontaneous Potential (XSP), Gamma Ray (XGR), caliper (XCAL); #3: depth meters along hole; #4: SNED, RM, RTED shallow, medium and deep resistivities; #5: Young´s modulus; #6: Poison´s ratio; #7: brittlness average (BA); #8: cotlog (total organic carbon content from logs), cotlab (total organic carbon content from laboratory); #9: volume of clay/shale/silt. Brittle intervals are displayed as red colored in track #7.

Conclusions

The geological properties of rocks, being them clastic, chemical or biochemical, influence reservoir quality and hydrocarbon’s production. Shales (mudrocks/limestones) from continental environments are by far complex because of their depositional nature and highly variable vertical and lateral sedimentary characteristics.

Lacustrine environments of the Cuyana Basin were developed under a strong tectonic and climatic influence and corresponded to mostly balanced and underfilled lakes. The evolution of these important water bodies were conditioned by the tectonic accommodation space repeatedly created along three reactivational pulses (Rift I, II and III). The initiation of shallow lakes corresponds to low accommodation stage of the basin (LAS) and the persistent highstand deep lakes during the high accommodation stage (HAS). Climate was first semiarid but seasonally humid and finally warm-temperate or sub-tropical. Hence playa–lake type and then perennial lakes were developed in the studied depocenters.

Marginal to deep off-shore facies show differences in mineralogical and textural composition that let to discriminate brittle to ductile layers and model a mechanical cyclicity along the Triassic lacustrine columns of the basin. Upscaling these features and properly model their vertical and horizontal variations, will contribute to the geomechanical studies and could help in horizontal wells location and in the stimulation designs, hence providing with detailed information to the optimization of fracture programs and to the prediction of possible associated geohazards.

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