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Unconventional Reservoir Geology of the Neuquén Basin Argentina

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Abstract

The Neuquén Basin is one of the most important hydrocarbon producing basins of Argentina and is presently being explored and restudied because of its unconventional reservoirs rocks. Since the basin resulted from thermo-mechanical processes acting on a structured lithosphere a geodynamic analysis was needed for interpreting the regional distribution of its depositional sequences and their associated unconventional reservoirs. This basin corresponds to a continental rift developed during differential intraplate stresses derived from a backarc extension. Most of the border fault systems consist of reactivated structures whose attitude with respect to the extensional regime controlled the geometry of the basin. The infilling consists of clastic and pyroclastic rocks sourced from continental alluvial-fluvial environments during Triassic to Early Jurassic times to alternative marine-continental during most of the Jurassic to Cretaceous times. This evolution is consistent with troughs growing larger through time but being affected by recurrent extensional pulses during accelerated basin subsidence and or seal level change overlapped by compressional forces which resulted in a complex environmental relationship throughout the basin. Consequently, vertical and lateral facies variations are present in reservoir rocks along the basin which requires a detail analysis to proper model the petroleum systems. Especially because significant hydrocarbon source rocks of this basin, that can be produced as unconventional, like the highly known Vaca Muerta Formation. The aim of the present contribution is then to propose an integrated, geodynamic and tecnostratigraphic model to the Neuquén Basin which can improve the understanding of its geological evolution particularly considering that the estimated resources related to unconventional reservoirs are 455 TCF.

Introduction

The need to increase hydrocarbon reserves challenges Argentina with a novel concept in oil prospecting. This challenge needs the implementation of new prospecting techniques and basin modelling for both locating and assessing potential petroleum systems and optimizing production resources. Forecasting the presence of source rocks, reservoirs, seals, overburden rocks, as well as the development of traps requires a thorough knowledge of the stratigraphic and structural evolution of the deposits within a sedimentary basin. This involves what is known as basin analysis which from a geodynamic point of view, helps understand how these large lithospheric structures —that contain hundreds of thousands of meters of sediment— are formed and how they are filled in (Barredo, 2012). When basins hold unconventional reservoirs the mechanical properties of the source rock must also be studied in detail. Their characteristically low permeability derives from the depositional history, the resulting mineralogy and the chemical conditions and all of them (Stinco, 2001), constrained by tectonic, eustatic and climatic variations. Thus, the sedimentary infill must be studied, from the tectonic/geodynamic and paleoclimatic approach, but focusing the reconstruction on the sequential arrangement of its elements.

There are six hydrocarbon producing basins in Argentina which covers 545,000 km2 (Fig. 1), among them the Neuquén Basin is considered one of the most profitable because it comprises 4 of the eleven source rocks with potential to be unconventional reservoirs. These rocks are mostly marine in origin but there are also shales from lacustrine environments (Fig. 2) (Barredo and Stinco, 2013).

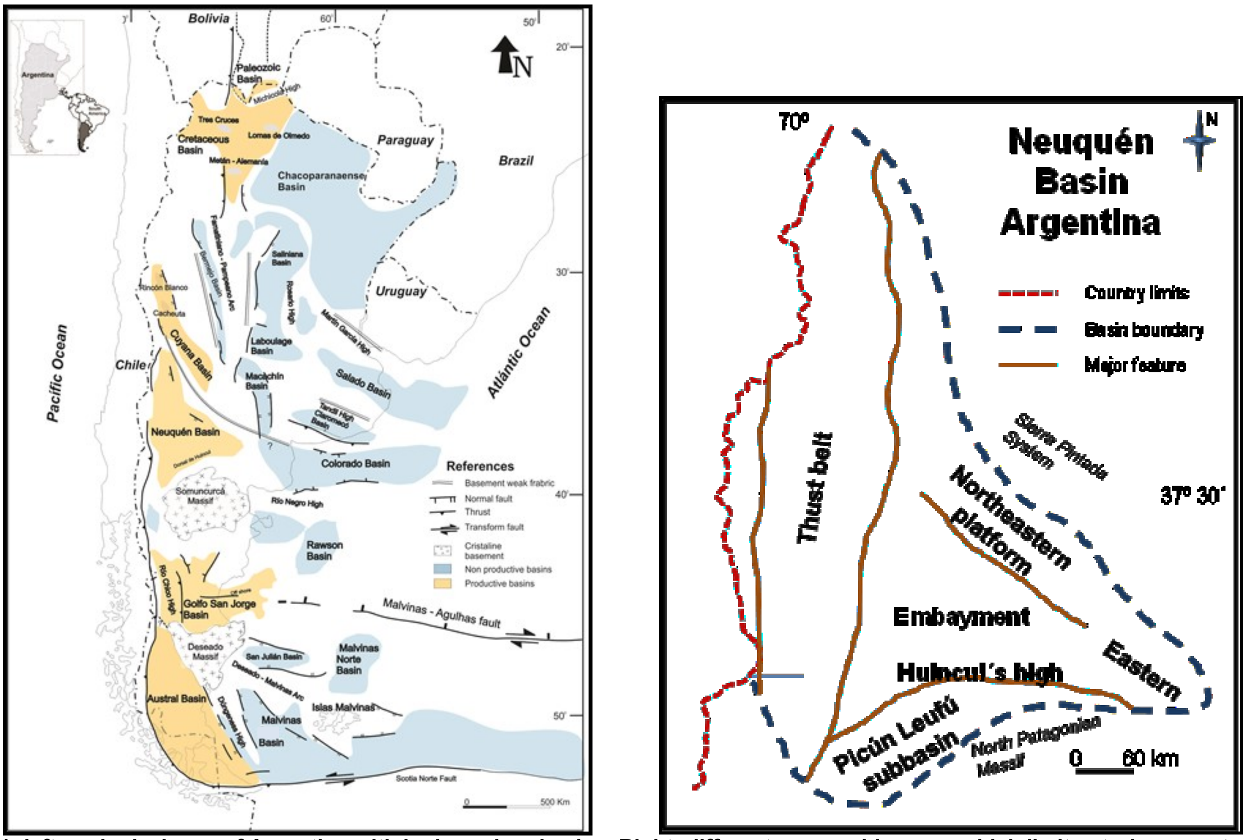

Figure 1: left geological map of Argentina with hydrocarbon basins. Right: different geographic areas which limit petroleum systems location.

Basin	Formation	Resources (TCF)
Paleozoic	**Los Monos**	**40**
Cretaceous	Yacoraite	5
Cuyana	**Cacheuta**	**15**
Neuquén	Precuyano	5
Neuquén	**Los Molles**	**190**
Neuquén	Vaca Muerta	220
Neuquén	**Agrio**	**40**
Golfo San Jorge	Neocomiano	20
Golfo San Jorge	**D-129**	**100**
Austral	Serie Tobífera	5
Austral	**Palermo Aike**	**160**
Total		**800**

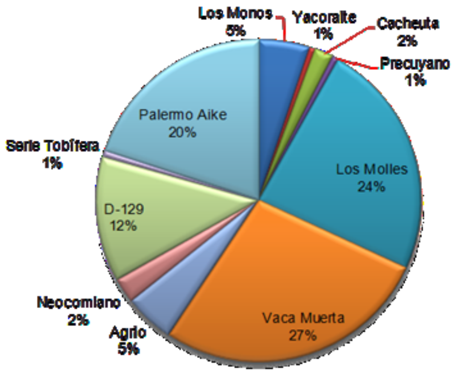

Figure 2: estimated resources by source rock (from Stinco and Barredo, 2014a).

The Neuquén Basin covers an area of 115,000 km^2. Being located at the west-central part of Argentina between 32° and 40°S latitude, its deposits comprise more than 7,000 m of continental and marine, mainly siliciclastic mixed carbonate sediments, with ages ranging from Late Triassic to Late Cretaceous /Early Cenozoic (Fig 3). This basin has been interpreted as a back-arc related to a prolonged connection with the paleo-Pacific which permitted several marine ingressions across the magmatic arc by Gulisano et al. (1984); Mitchum and Uliana (1985); Legarreta and Gulisano (1989) and Legarreta et al. (1993) all of them driven by sea-level variations and/or tectonics (Barredo and Stinco, 2013).

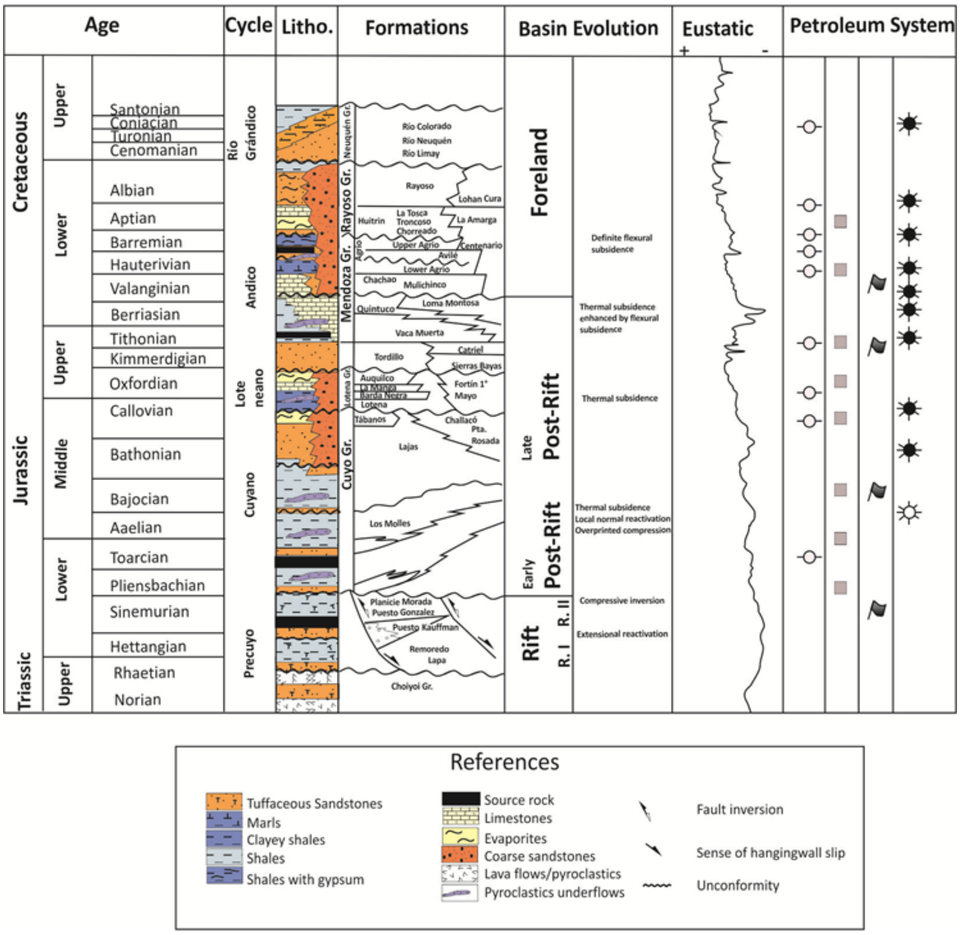

Figure 3: stratigraphic column, tectonic history, eustatic changes through time and the petroleum system elements. Modified from Mitchum and Uliana (1985), Legarreta and Gulisano (1989), Legarreta et al. (1993), Vergani et al (1995), Fernandez Seveso et al. (1996), Barredo et al. (2008), Barredo and Stinco (2013) and Stinco and Barredo (2014a).

Main basin hydrocarbon fields are located in the subsurface of the embayment starting with Precuyo during the extensional opening of the basin. Major cyclic events related to these sea oscillations provided the proper marine environment conditions to promote the development of several other source rocks within the basin. The Los Molles Formation (Lower to Middle Jurassic) was deposited under the first marine event above the synrift continental deposits of the Precuyo. The other one is the Vaca Muerta Formation, presently the most important source rock of the basin that covers at least 25,000 km^2 of the Neuquén basin and spans from Lower Tithonian (147 ma) to Lower Valanginian (135 ma) (Leanza, 2012). The last one is the Agrio Formation (middle Early Cretaceous) much more areally restricted than the underlying.

The aim of this paper is to characterize the unconventional reservoir rocks of this basin using the integrated information from geodynamics and tectonostratigraphy to understand its geological evolution which was strongly conditioned by the tectonic behavior of the Pacific margin of Gondwana. Considering that the estimated resources related to unconventional reservoirs are 455 TCF, arriving to a more precise model of the geology of the source rocks will contribute to characterize their temporal and spatial anisotropies.

Geological setting and stratigraphy

The Neuquén basin has a broadly triangular shape and exhibits different geographic areas, like the thurst belt to the west (Aconcagua, Marlargtie and Agrio), northeastern platform, embayment in the center and coincident to the depocenter, the easternmost area, the Huincul´s High and the Picún Leufú sub-basin to the south (see Figure 1). Its origin is closely related to the evolution of the western margin of Gondwana during Middle Permian to Early Triassic when an extensional period derived from the declining and/or cease of the long-lived subduction of the Panthalassan (Llambías and Sato, 1995). It was a characteristic silicic event named Choiyoi Group interpreted as the result of the collapsed of the Permian orogeny e.g. (Uliana et al., 1989; Llambías and Sato, 1995) and/or the beginning of the Pangea breakup e.g. (Uliana et al., 1989). By Early to Middle Triassic, deformation focused on the Gondwana western margin from the north portion up the 32° latitude but in Late Triassic to Early Jurassic times, the inception of a new juvenile magmatic arc associated with the renewal of the subduction processes, added extra intraplate extensional forces further south, along most efficient litospheric weakness (weak material)(e.g. Hervé and Fanning, 2001; Llambías et al., 2007; Barredo, 2012). An oblique tectonic regime was developed (Barredo, 2012) which led to an extensional tectonics and the evolution of a series of narrow, isolated depocenters (Manceda and Figueroa 1995; Vergani et al. 1995, Franzese and Spalletti 2001, among others) in a rapidly subsiding, fault-bounded, back arc-related wide trough (see Fig.1).

Field studies and seismostratigraphic analysis show that changes in sequence geometry occurred in-phase with this intra-continental elastic stress relaxation, as fault reactivation during rifting but also as a result of compression derived from Huincul High uplifting and localized inversion (Barredo et al., 2008). Two rift stages were developed (Fernandez Seveso et al, 1996; Barredo, et al., 2008) that were filled by a complex array of clastic (continental - marine) and volcaniclastic deposits. Continental deposits are grouped in the Precuyo Cycle completely developed during rifting (Rift I and II). It holds the only lacustrine source rock of the basin, Puesto Kauffman Formation. During the climax of the second (Rift II), a series of transgressive-regressive (T-R) marine cycles, controlled by the combined effects of changes in subsidence rates, localized uplift and eustatic sea-level oscillations, were developed. The first marine depositional episode of the Cuyo Group took place (Early-Middle Jurassic), this transgressive event corresponds to the Los Molles Formation) and was followed by a regressive episode with the development of shallow marine to continental environments (Lajas, Challacó and Tábanos formations) (Weaver, 1931; Gulisano et al.,1984; (Zavala, 2002; Zavala and González, 2001) (see Fig. 3). During climax and early post rift, the Lotena and Mendoza groups were deposited; in both transgressive marine realms evolved but only the blacks shales of the Vaca Muerta (Tithonian to Valanginian) and Agrio (Valaginian – Barremian) formations of the Mendoza Group, are source rocks (Stinco and Mosquera, 2003) (see Fig. 3).

Along the Cretaceous and the Tertiary the opening of the Atlantic markedly accelerated South America westward motion and together with the convergent motion during the collision of the oceanic ridge transformed Andes into a convergent arc whose compression lightly loaded the craton with the resulting increment in the accommodation space. The ancient continental rift basin was subjected to compression and foredeep deposition as it was forced to close. A new configuration was achieved as a consequence of flexural subsidence induced by the Andean orogenic overloading and by sediment charge all along the Tertiary period (Barredo and Stinco, 2013).

Integrated tectonosedimentary analysis of the unconventional reservoir rocks

The Neuquén basin is a wide through with embayment morphology, roughly triangular in plan view, filled with marine and continental sediments. Drainage systems were controlled by sea and local stratigraphic level (mostly lakes). In this scenario, the relationships among incremental accommodation space, associated with tectonic and/or eustatic subsidence, sediment plus water supply and short-time climatic influences determined which depositional system predominated. The geometry consists of border faults which mostly strike obliquely to the maximum extension direction and have a stepping design. During rifting, restricted half-grabens were formed and filled with a second-order pile of 7,000 all of them corresponding to alluvial, fluvial, lacustrine, deltaic and pyroclastic deposits (e.g. Uliana et al., 1989; Gulisano and Gutierrez Piembling, 1994; Barredo et al., 2008; Barredo, 2012; Drosina et al., 2010). Differential increase in thickness towards the border faults suggests that these structures were syndepositionally active and in fact, the switch from major fluvial to lacustrine environments along the basin has been interpreted to reflect tectonic activity.

According to the tectonic pulses registered for the Gondwana margin, two rift stages have been reported by Fernandez Seveso et al. (1996), Barredo et al., (2008), among others. The transition from the rift climax to the early post-rift started in Middle Jurassic, coetaneous with the first marine ingression (Los Molles Formation) while the definite thermal relaxation of the post-rift stage occurred in the upper Middle Jurassic (Gulisano and Gutierrez Piembling, 1994; Barredo et al., 2008). Both stages were overlapped and affected by a northwest trending compression which produces synchronous inversion in several extensional border faults and locally controlled the petroleum systems (e.g. Vergani et al., 1996; Barredo et al., 2008).

All of these rift phases display characteristic depositional environments with one or more elements of the petroleum system. During first stages of rifting, alluvial to fluvial deposition predominated (Precuyo Cycle) with strata progressively onlapping the hanging-walls of the because sediment supply exceeded the incremental accommodation space (basin overfilled), 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 (e.g. Uliana et al., 1989; Vergani et al., 1996; Barredo et al., 2008; Rincón et al., 2011) (Fig. 4). The gradual faults growth in length and displacement along time permitted depocenters to increase in depth, length, and width and thus, the incremental accommodation space through time. 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. Contemporaneously volcanism shed huge amount of pyroclastics (tuffs and flows) materials into the basin (Fig. 5) (Barredo et al., 2008)

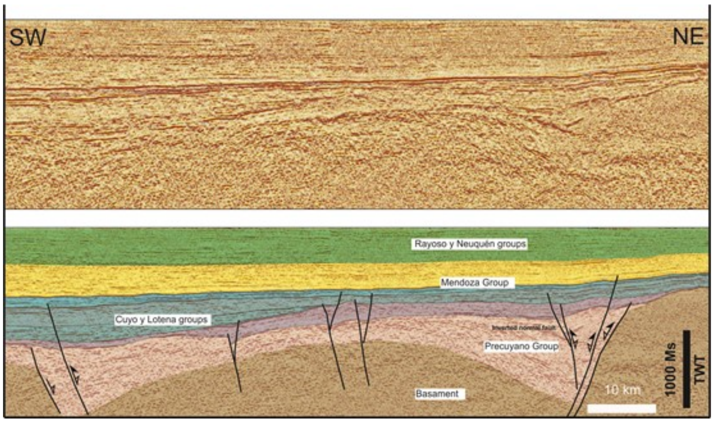

Figure 4: seismic lines uninterpreted (upper), interpreted (lower) corresponding to a cross section of the embayment. Note the characteristic asymmetric infilling of the rift stage sediments. It corresponds to the Precuyano Cycle with the lacustrine source rock. Deposits of the marine ingression come from de west southwest pinchout towards the east margin. Cuyo and Mendoza groups hold the producing Vaca Muerta and Agrio source rocks (from Barredo et al., 2008).

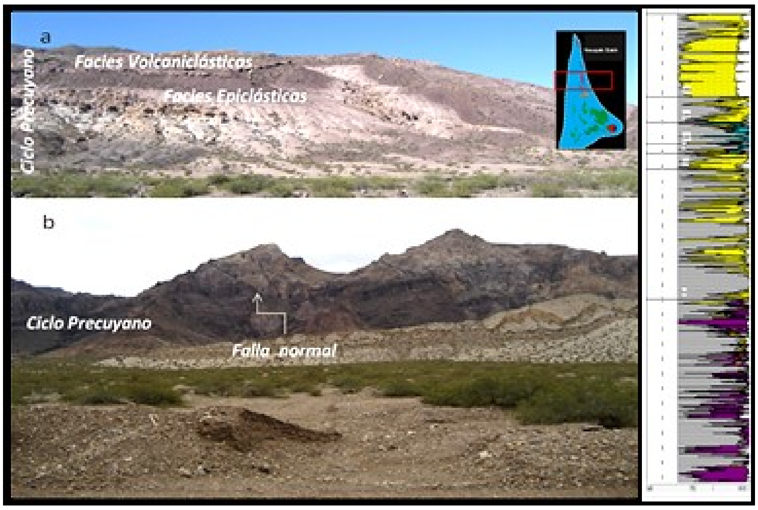

Figure 5: upper picture shows outcrops of pyroclastic rocks of the Precuyano Cycle in the Cara Cura depocenter (northern margin of the Neuquén Basin). See location map at the right of corner, in green, red an orange different depocenters of the basin during the rifting stage, lower picture depicts normal faults in still preserved hemigrabens. Note that they are infilled with alternating sandstones, black shales (source rock) and pyroclastics. To the right, estimated percentages of volcaniclastics (purple), siliciclastics (yellow), carbonates (blue) and shales (gray) in a well drilled in the middle of the depocenter (red dot in map).

According to this scenario, the first stages of the infilling of the Neuquén Basin (Precuyano cycle) proved to be very complex. Unconventional tight reservoirs are associated with pyroclastic rocks whose potential seemed to be related with the rheology of the pyroclastic flows, their cooling history and hydrothermal alteration (Drosina et al., 2010). These flows and its potential reservoir characteristics are especially true in low welded ignimbrites that display evidences of deutheric alteration linked to vapor phase crystallization of the gas pipes infilling which resulted in the enhanced reservoir properties observed in several depocenters (Drosina et al., 2010).

On the other hand, interfingering shales produced in strongly cyclic lakes are presently source rocks and potential unconventional reservoirs of the basin. During maximum space creation, depocenters were completely underfilled and so hydrologically closed lacustrine, playa type deposition evolved under a semiarid seasonally humid climate (Barredo and Stinco, 2013). These lakes were located close to the faults and subjected to climatic base-level fall-to-rise turnarounds and thus show a marked cyclicity especially those which were balanced. Bioproductivity was local and the maintenance of suboxic bottom conditions was mainly dependent on the topography. Kaufman shales are presently source rocks, and has a TOC that varies from 2 to 11%, Romax (%) 0.4 to 0.8, Hydrogen Index up to 900 mg HC/gTOC, SPI from 10 t HC/m2, kerogen type I to mixed I/III and a Visual Kerogen Analysis (VKA) (Legarreta and Villar, 2011) suggesting significant terrestrial woody input over the algal lacustrine production. Thickness ranges from 50 to over 1,000 meters as a consequence of the marked rifting topography. The majority of wells that reached the Precuyano are located to east and center of the basin with many of them with oil and gas shows. Volume estimation assigns 2 to 5 TCF to this formation (conventional Puesto Kauffman reservoir).

The extensional phase was pulsatile with important reactivations at least up to Lower (Middle?) Jurassic (Fernández Seveso et al., 1996; Barredo et al., 2008). During this tectonic phase marine and continental facies were deposited (Legarreta and Gulisano, 1989) under eustatic and tectonic controls (Los Molles and Lajas formations of the Cuyo Group). Subsidence continued as a consequence of this second rift stage after which the basin started to evolve into a post rift stage. An expansion of the marine realm flooded the basin from the west by repeated drowning through openings in the arc (Uliana et al., 1989; Llambías et al., 2007; Gulisano y Gutierrez Piembling, 1994,Spalletti, 2000; Legarreta et al., 2005; Howell et al., 2005, Barredo and Stinco, 2013, among others) giving place to the development of the several significant source rocks and presently unconventional reservoirs of our country, Los Molles and Vaca Muerta formations while the definite thermal relaxation permitted the deposition of the Agrio Formation, still under marine conditions. Climate was first semiarid seasonally humid but by Middle Jurassic it was warm to temperature with wet-dry cycles, warm and dry in the Upper Jurassic and more humid during the Cretaceous. Post-rift subsidence was disturbed by repeated inverse reactivation of the ancient extensional faults associated with the uplifting of the Dorsal de Huincul (Huincul´s High) during Jurassic times and the change to a retroarc flexural subsidence during the foreland stage that have occurred from the Cretaceous times onwards. Consequently, both eustasy and tectonism (subsidence rate and localized uplift) helped to control these source rocks deposition and preservation while the high lands of the eastern portion of the basin generated by the inversion of ancient Triassic faults, limited marine ingression to the hinterlands.

First ingression is represented by Los Molles Formation and according to Barredo et al. (2008) that positive areas close to the Huincul High, limited the marine ingression of this unit the east and the inherited topography conditioned its deposition to different throughs. This formation exhibits well developed shallow marine environment with moderate oxidizing conditions influenced by fluvial discharge that pass to shelf and partially restricted environment to deep-water turbidite systems with significant pyroclastic underflows (LLambías et al., 2007; Barredo, 2012) and finishes as shallow marine. The Los Molles Formation is the second most important unit in the basin. It has a TOC that varies from 1 to 5%, Romax (%) 0.8 to 2, Hydrogen Index 300-500 mg HC/gTOC, SPI of 6 t HC/m2, kerogen type II-III and a VKA of algal amorphous with variable terrestrial contribution (Stinco and Mosquera, 2003; Legarreta and Villar, 2011) (Fig. 2). Thickness of Los Molles Formation ranges from 100 to 800 meters. This unit presents also tight reservoirs widespread distributed within the formation being controlled by the paleotopography and the channelized submarine fans. Thousands of wells have penetrated partially and hundreds totally the formation as part of the exploration and development of the basin. Most of them have oil and gas shows and in many cases there is consistent production of hydrocarbons. Current development of unconventional reservoirs is focused on tight gas and oil reservoirs mainly encountered within the vicinity of the depocenter of the basin, mostly related to gas prone basin centered gas systems. Volume estimation assigns 130 to 190 TCF to this formation (Barredo and Stinco, 2013).

The Vaca Muerta Formation is the most important source rock in Argentina. It's geological and petrophysical variations (Stinco, 2001) are significantly linked to the geodynamic history of the basin strongly related to the transition from the last rift reactivation to the definite thermal relaxation of the post-rift. As a consequence, it overlies with sharp contact the continental deposits of the Tordillo and Quebrada del Sapo formations during the Tithonian transgression (see Fig. 3). The characteristic dark grey, organic-rich shales of the Vaca Muerta Formation were deposited in a deep-water environment in the western and middle sections of the basin that passes laterally and to the east to calcareous sandstones and limestones of a weel developed shelf. Sedimentologically, this unit is characterized by a stacked rhythmic alternation of marls, black shales and limestones related to an external ramp with restricted conditions (Spalletti et al., 2000; Scasso et al., 2002, Stinco and Mosquera, 2003, among others) distributed as depositional sequences with proximal facies prograding to the west (Mitchum and Uliana, 1985; Legarreta and Gulisano, 1989) where sandy gravitational flows developed in deep and steep portions of the basin. Additionally, local controls existed because ancient extensional fault were still active presumably under late elastic relaxation (Stinco and Barredo, 2014a, Stinco and Barredo, 2014b). The notable high frequency cyclicity of this formation is associated with systematic changes in productivity on the sea surface, and supply of terrigenous and non-terrigenous material in suspended plumes under Milankovitch cycle range.

From a total of 800 TCF of estimated resources, around 27% (220 TCF) are assigned to Vaca Muerta Formation (Stinco and Barredo, 2014). It has a TOC that varies from 3 to 8%, Romax (%) 0.8 to 2, Hydrogen Index 400-800 mg HC/gTOC, SPI 5 to 20 t HC/m^2, kerogen type I-II and IIS in marginal areas, and VKA of high quality amorphous (Stinco and Mosquera, 2003; Legarreta and Villar, 2011) (Fig.2). Thickness of the Vaca Muerta Formation ranges from 25 to 450 meters covering an area of at least 25,000km^2. Thousands of wells have penetrated partially or totally the formation as part of the exploration and development of the basin. The majority of them has oil and gas shows and in many cases there is production of hydrocarbons. Since 2010 different companies started to drill exploration wells targeting the unconventional oil and gas shales of Vaca Muerta Formation. Its world class source rock characteristics has mobilized the economic activity within the basin and more than 250 wells have been drilled with initial productions of 95 bbls/day for horizontal ones and 42 bbls/day for the vertical wells. Although there is a limited production history, EUR @ 25 years for the vertical wells are 176,000 bbls while for the horizontal ones around 300,000 bbls. Current oil production is around 20,000 bbls /day. Volume estimation assigns 170 to 220 TCF to this formation.

The last Pacific ingression corresponds to the Agrio Formation (middle Early Cretaceous) which took place during a significant change in the subsidence regime: the gradual and pulsatile transition to the foreland phase under a dry climate (Barredo and Stinco, 2010). It consists of thinly laminated shales of dysoxic environments and olive-grey and dark-grey shales, and massive mudstones (silty claystones and silt-stones), of definite anoxic conditions both deposited in outer ramp. Well preserved storm dominated shallow marine facies are preserved with mixed siliclastic and carbonate sedimentation represented by packstones, wackestones and calcareous sandstones alternating with thin coquinas, siltstones or fine-grained sandstones. Upward coaersening of sediments is represented by alternating olive-grey mudstones and fine- to medium-grained sandstones or coquinas of mid-ramp setting.

The Agrio Formation has a TOC that varies from 2 to 5%, Romax (%) 0.6 to 1, Hydrogen Index 300-700 mg HC/gTOC, SPI from 4 to 12 t HC/m^2, kerogen type II to II-III and a VKA of algal amorphous with variable terrestrial contribution (Legarreta and Villar, 2011) (Fig.2). Thickness of the Agrio Formation ranges from 50 to 400 meters. Hundreds of wells have reached the formation as part of the exploration and development of the basin. Oil and gas shows were documented in many cases as well as production of hydrocarbons. Current development of unconventional reservoirs is focused to the west and north of the basin. Volume estimation assigns 20 to 40 TCF to this formation.

Figure 6 shows areal distribution of the Puesto Kauffman, Los Molles, Vaca Muerta and Agrio formations in the basin. Since 1918 there is hydrocarbon´s production in Neuquén Basin, having being discovered more than 5 $x10^9$ barrels of oil and 3.2 $x10^{13}$ scf of gas.

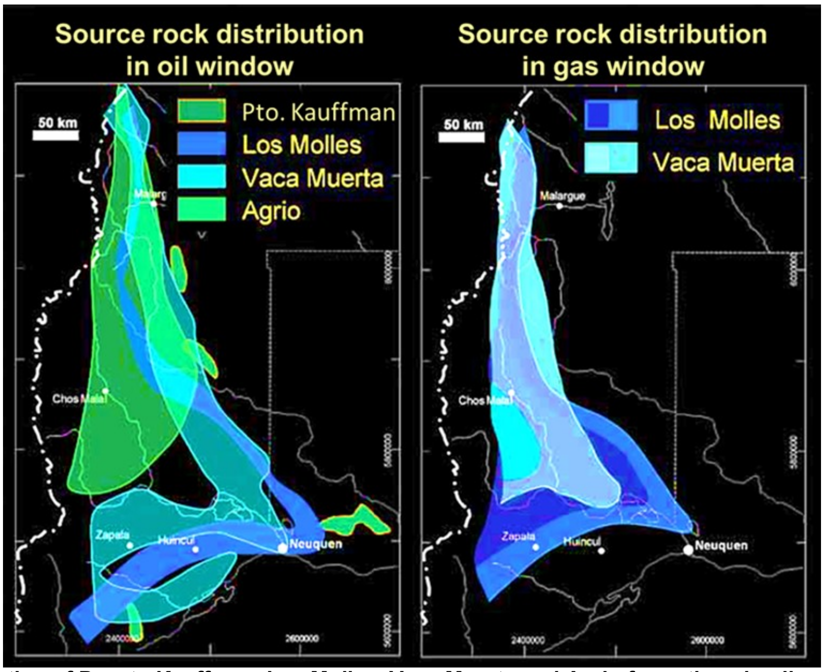

Figure 6: areal distribution of Puesto Kauffman, Los Molles, Vaca Muerta and Agrio formations in oil and gas windows (modified from Legarreta and Villar, 2012)

Conclusions

Unconventional shale reservoirs of the Neuquén Basin are strongly related to geodynamical context of the Gondwana margin. It is a back-arc basin whose infilling followed the dynamics of the convergent margin and the magmatic arc. Changes in sequence geometry occurred in-phase with the intra-continental elastic stress relaxation. Faults undergone extensional and compressional reactivation during rifting and also during the uplifting of the Huincul High. Thus, each rifting stage changed the geometry and space for sedimentation which in turn conditioned shale deposition and organic matter preservation under different climates. Moreover, shales display low permeability derived from the depositional history, the resulting mineralogy and the chemical conditions which are at the same time constrained by tectonic, eustatic and climatic variations. Thus, the sedimentary infill must be studied, from the tectonic/geodynamic and paleoclimatic approach, but focusing the reconstruction on the sequential arrangement of its elements.

Finally, all of the presently source rocks like, Puesto Kauffman, Los Molles, Vaca Muerta and Agrio formations can be considered unconventional reservoirs due to the large non expelled volume of hydrocarbons that they record. The reason why it is so rests on multiple factors but one of the most relevant seemed to be the oblique convergence and the consequent strain partitioning operating over a reworked lithosphere with a strong controlling fabric from the Paleozoic onwards. Understanding the Gondwana margin geodynamic evolution is necessary to model the basin for predicting the existence or absence of oil and gas prone shales among different depocenters.

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