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The Vaca Muerta Formation (Late Jurassic - Early Cretaceous), Neuquén Basin, Argentina: Sequences, Facies and Source Rock Characteristics

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Summary

The geological characteristics of the Vaca Muerta Formation, in terms of thickness, areal extent, depth, organic-content, thermal maturity level, mineralogical composition, hydrodynamic conditions and structural framework made this unit a world-class source rock, very appealing for unconventional resources.

The accumulation of the marine organic-rich facies of Vaca Muerta Formation took place in a backarc depocenter, known as Neuquén Basin, connected to the Pacific. This time-transgressive interval is currently the main target for unconventional resources and can reach over 300 m, distributed within two sequence-sets (Kimmeridgian-Late Tithonian and Late Tithonian-Early Valanginian), associated to 2nd order cycles. The highest TOC content, up to 12%, is associated with the 2nd order transgressive sequence-sets but thinner intervals with less areal distribution developed during the maximum flooding of 3rd order sequences. Thickness, facies composition and distribution of the source rock intervals vary in the basin according with the sequence analyzed. Also the basin bottom configuration, affected by the presence of arcs and highs had influence on the water circulation favoring different degree of restriction, from anoxic to euxinic conditions.

Present-day knowledge of the facies composition and geochemical characteristics of the Vaca Muerta source rock are based on outcrop sections and well data correlated with seismic data (2D and 3D). The volume of information obtained with the current activity is increasing very fast but not with the same level in different positions of the basin. The source and related key facies for unconventional resources show slightly different regional distribution for each sequence-set. In the SE corner of the basin and central position of the so-called Neuquén Embayment, the Early-Middle Tithonian source dominates. This interval thins down and suffers a facies change toward W and NW, whereas the Late Tithonian-Early Valanginian gets importance in terms of thickness, increasing its source quality as well. Exploration/development effort for oil shales is mainly circumscribed on the older Vaca Muerta section and the current results cannot necessarily be the same for the younger interval.

Introduction

Since few years ago the Vaca Muerta Fm has been the main target for unconventional resources in Argentina, and exploration/development activities are particularly focused on the Neuquén Embayment (Fig. 1). Present-day knowledge, based on previous studies, indicates that Vaca Muerta is made up of several stratigraphic units (sequences) with different areal distribution and composition. The results obtained in a particular zone of the basin could not be extrapolated to other areas.

The Neuquén Basin is located in west-central Argentina (Fig. 1) and the sedimentary column with economic potential is mostly preserved just on the eastern flank of the Andes and foredeep area. During Late Jurassic and Early Cretaceous the back-arc depocenter was governed by a sag tectonic regime, while the western side of the South American plate evolved as a convergent margin, connected to the Pacific through an active magmatic arc

(Legarreta and Uliana, 1991). Eustatic oscillations in the Neuquén Basin, under this dynamic tectonic scenario, allowed to generate events of desiccations, with accumulation of evaporites and non-marine clastics, many times followed by fast marine flooding that covered the basin; during these stages several thick organic-rich shales intervals (Fig. 1) accumulated under anoxic to sub-toxic conditions (Legarreta, 2002).

Sequence stratigraphic analysis of Vaca Muerta Fm and time-equivalents units was performed in the subsurface of the Neuquén Embayment by Mitchum and Uliana (1982; 1985) and based on outcrops by Gulisano et al., (1984) and Legarreta and Gulisano (1989). A study of the Late Jurassic to Early Cretaceous column that covers the whole basin, using 2D seismic, wells and outcrop sections with ammonite control was performed by Legarreta and Uliana (1991; 1996). The chronostratigraphic chart is based on the studies of the ammonite record performed by Leanza (1981), Riccardi (2008) and Aguirre Urreta et al. (2005). There are additional papers dealing with the stratigraphic framework associated with Vaca Muerta unconventional resources in a Symposium recently organized by Galeazzi et al., (2014) that show stratigraphy, facies, mineral composition and several key topics, as result of the exploration/development activity performed during the last 5 years.

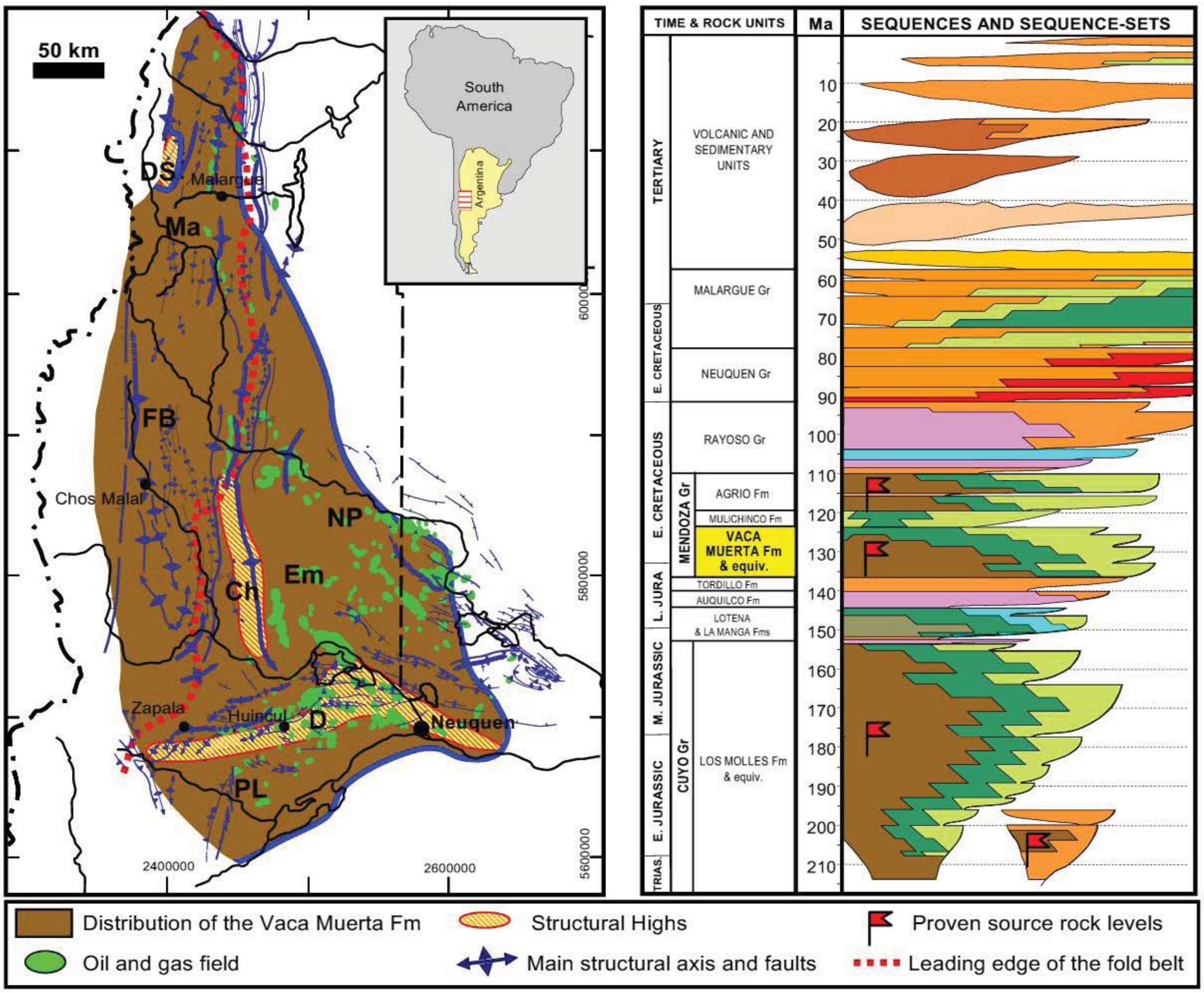

Figure 1. Left: distribution of the Vaca Muerta source rock, main structural axis, leading edge of the fold belt, oil and gas fields and some key structural highs that were active during the Jurassic and Cretaceous. Key areas mentioned in the paper: DS=Dedos-Silla High, Ma=Malargüe, FN=fold belt, NP=North Platform, Em=Embayment, Ch=Chihuidos High, D=Huincul Dorsal, and PL=Picún Leufú Depocenter. Right: Chronostratigraphic chart indicating main sedimentary cycles (sequences and sequence-sets) and the stratigraphic location of the Vaca Muerta source

Stratigraphy and Facies

The Vaca Muerta Fm, mainly consisting of marine dark organic-rich shales, is present within a stratigraphic interval composed of two sequence-sets related to 2nd order cycles (Legarreta and Villar, 2013), developed from the Early Tithonian to Early Valanginian (Fig. 2). In the Neuquén domain the Vaca Muerta changes from the basinal shales to shallow marine carbonates and clastics named as Quintuco and Loma Montosa Fms (Mitchum and Uliana, 1985) and in the Malargüe domain is represented by the shelfal and nearshore carbonates known as Chachao Fm (Legarreta et al., 1981).

Existence of paleo-highs within the basin (Fig. 1), like Dedos-Silla (DS), Chihuidos (Ch) and Huincul Dorsal have shown variable activity during Jurassic and Cretaceous. They had less subsidence and/or acted with a relatively strong positive tendency during the accumulation and for that reason a very thin section (or condense interval) was recorded over the top of the highs. In some cases the discontinuities among sequences, or sequence-sets, display a truncation relationship, indicating local tectonic enhancement. The effect of this process can be observed along different zones of the Huincul Dorsal and Dedos-Silla trends (Fig. 1 and 3).

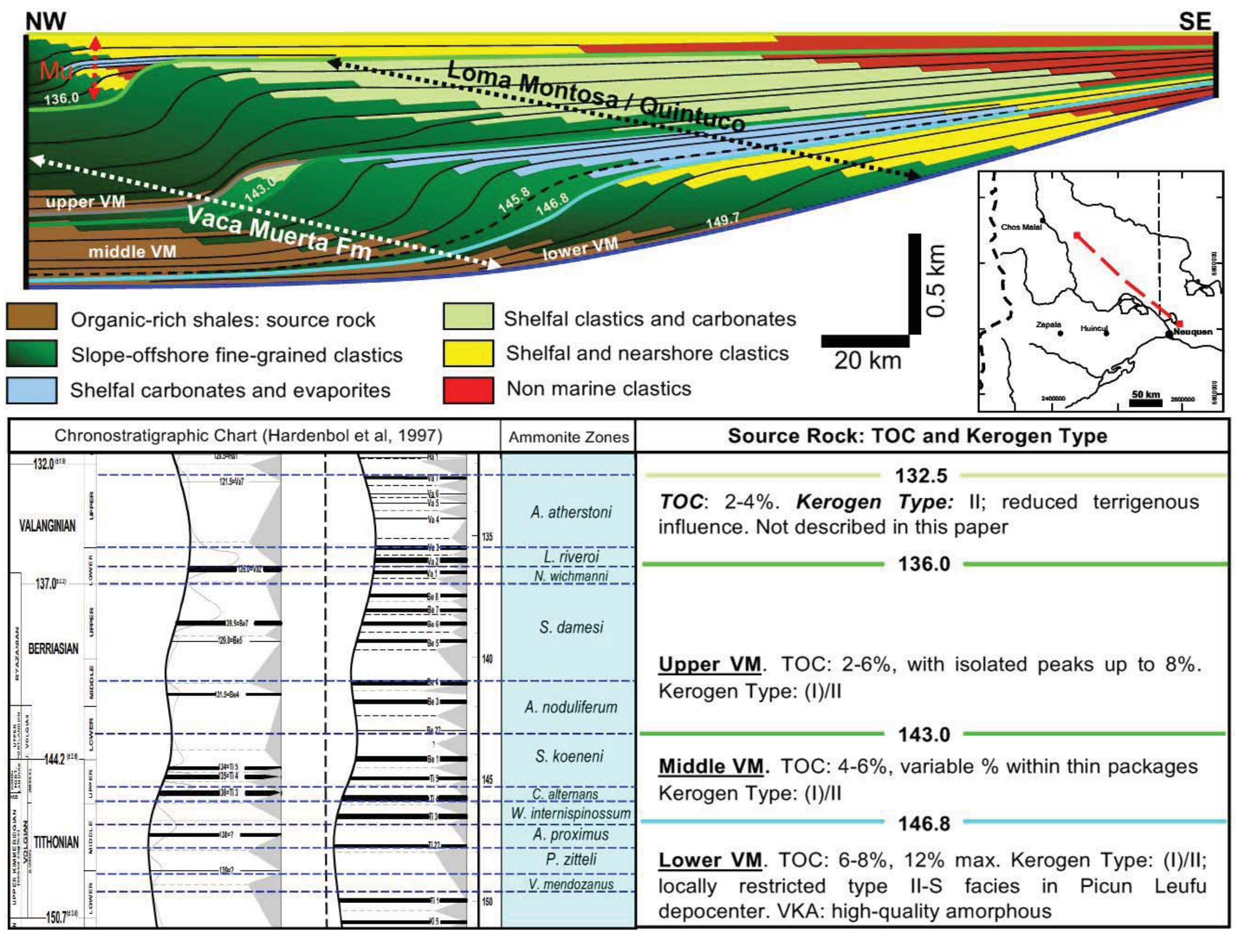

Figure 2. Upper: Schematic cross-section illustrating internal configuration, main sequence-set boundaries, numerical ages, facies and lithostratigraphic nomenclature (Mu=Mulichinco Fm). Lower: Chronostratigraphic chart indicating 3rd and 2nd order cycles and ammonite biozones used to date units within this interval. A description of the Total Organic Carbon (TOC) and Kerogen Type is included for the three informal Vaca Muerta sections. The uppermost organic-rich interval is not included in this paper

Within the Early Tithonian-Early Cretaceous interval (149.7-143.0 Ma), two sequence-sets were identified, each one involving a period of time of 6 and 7 Ma. Also, the lower sequence-set (149.7-143.0) can be subdivided in two intervals to better illustrate the evolution of sedimentary fill of the basin. The older unit (149.7-146.8 Ma) begins with a very fast marine flooding represented in the whole basin by a 0.5-1.0 m level of microbial bindstone associated with same ammonite specimen (*Virgatosphinctes mendozanus*). This basal section is transitionally overlaid by at least three depositional sequences that display a gentle sigmoidal geometry observed on seismic (Mitchum and Uliana,

1985) and in outcrops as well (Fig. 4), as shown by Massaferro et al. (2014). Dominantly composed by shelfal to nearshore clastics that change basinward to dark shales (Fig. 3), accumulated under anoxic conditions and in the Picún Leufú depocenter dominated by euxinic conditions (Fig. 1). In the slope and basinal setting sandstone packages are present as lowstand deposits, some of them recently tested within the Picún Leufú domain (Santiago et al., 2014). Toward a more distal position, there are thin-beds (less than 4 cm) of sandstones interbedded with the black shales.

The organic-rich shales developed within this group of sequences, regionally display a thickness less than 50 m with higher values along the western side of the basin. The Picún Leufú area (Fig. 1 and 6), where the lower Vaca Muerta can reach a thickness higher than 100 m. This zone behaved as a partially silled depocenter due to the presence of the Huincul Dorsal that acted as an irregular but continuous high interposed between the Neuquén Embayment and the southern platform. Under this scenario the restriction to the water circulation on the sea bottom favored the existence of euxinic conditions.

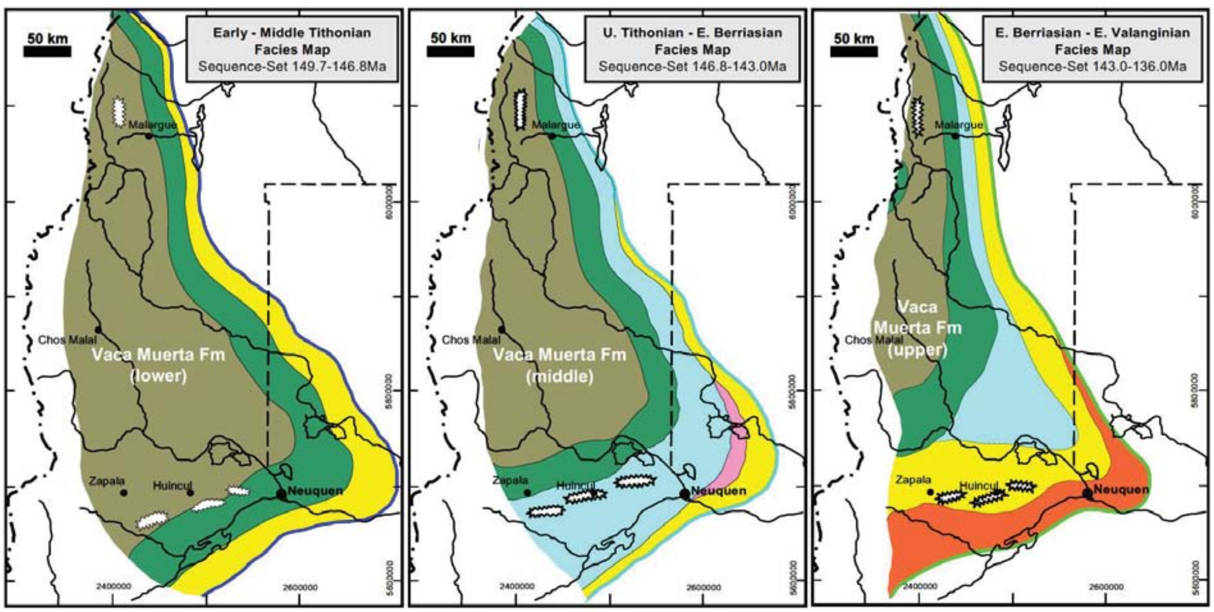

Figure 3. Paleogeographic maps illustrating facies distribution for the key sequence-sets analyzed in this paper (based on Legarreta and Uliana , 1991). Mapped intervals can be observed in the schematic cross-section (Fig. 1)

Although the lower sequence-set initially accumulated in a setting with an important accommodation space associated to a relative sea-level rise, this situation gradually change due to a slightly decrease of the available space during the Upper Tithonian to Early Berriasian when the next group of sequences (146.8-143.0 Ma) developed (Fig. 2). In response to a relative highstand to slight sea-level fall the internal sequence configuration display a noticeable complex-oblique pattern (Mitchum and Uliana, 1985). Recently, this interval was mapped in detail within the Neuquén Embayment by Pose et al. (2014) and Dominguez et al. (2014), based on the 3D seismic data and wells (Fig. 5). Under this new accommodation conditions, the main focus of accumulation migrated toward the basin with development of thick and steeper slopes and relatively thin shelf facies due to the reduced aggradation (Fig. 2). On the shelf environment, carbonates developed laterally associated with nearshore dolomites and evaporites, mostly present on the eastern Neuquén platform (Fig. 3). The slope facies is dominantly made of very fine-grained clastics, mud-supported carbonates and marls and gradually change toward the basinal setting to organic-rich shales with an important TOC content but, in general, lower than in the initial sequence-set.

Several 3rd order depositional sequences were identified and mapped (Pose et al. 2014, Dominguez et al. 2014), which helps to visualize the evolution of the basin fill and allow to individualize the intervals bearing key facies for unconventional exploration. Most of the slope and shelfal sediments are identified as Quintuco/Loma Montosa Fms in the Neuquén domain and Chachao Fm in the Malargüe area, and the basinal facies bearing source rock character within this interval, is informally named as middle Vaca Muerta. The internal configuration of these sequences, facies composition and ages based on ammonite content can be also observed in outcrops (Fig. 5). Current detail studies will provide new insights of this interval, particularly in the Neuquén Embayment where a series of NW prograding 3rd order sequences laterally change in relative short distance.

Compared with the lower Vaca Muerta, the middle section shows a slightly reduced areal distribution but reaches an important thickness (Fig. 6). In the Neuquén Embayment (Fig. 1), a key area for exploration/development of unconventional resources is over 200 m and increases toward the western side of the basin, just to the west of the Chihuidos High (Fig. 1), that acted as a relative less subsidence structural trend. In the Malargüe area, between the Dedos-Silla High and the eastern platform (Fig. 1), an important thickness (Fig. 6) coincides with the so-called axis Atuel-Los Blancos depocenter, a very deep NW-SE elongated Triassic-Jurassic halfgraben.

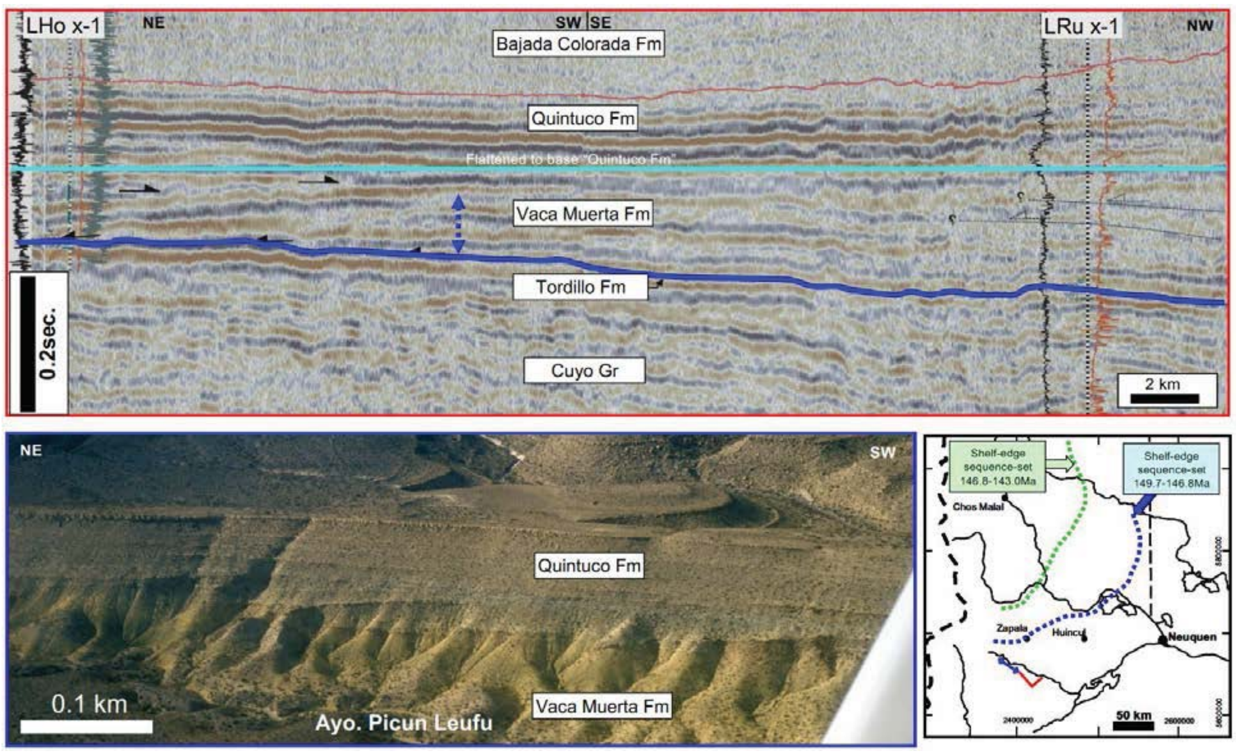

Figure 4. Upper: Seismic line running close to the outcrops in the Picún Leufú area (red line in location map) showing the internal stratal pattern and lowstand wedges (modified from Santiago et al., 2014). Lower: Oblique view of the Picún Leufú outcrops (blue line in location map) illustrating the progradational pattern (from SW to NE). At the base of the outcrops, partially covered, the organic-rich shales are present

The end of the first second order cycle is punctuated relative to a sea level fall indicated by the presence of a prograding complex that can be observed on seismic beyond the shelf break of the last sequence (Fig. 5) and this discontinuity developed around the limit between the *S. koeneni - A. noduliferum* ammonite zones, that is near to 143 Ma boundary. The following sea level rise provides a huge accommodation space and was responsible of a new marine flooding, covering the previous units by a widespread shaly interval in the whole basin. On the platform area it provided a key sealing element for the underlying dolomite and carbonate reservoirs, and toward the slope and basinal setting it favored the development of anoxic conditions provoking the accumulation of the upper Vaca Muerta organic-rich shales (Fig. 2).

The early sequences of the Early Berriasian to Early Valanginian (143.0 to 136.0 Ma) interval are relatively thin and display a gentle downlap pattern on the shelf setting associated with the mentioned shaly section at the base of this sequence-set. The internal configuration of this interval changed according with the evolution of the relative sea-level within a second-order cycle. It means, from highly aggradational pattern (transgressive) to a progradational configuration, in response to a highstand followed by a lowstand.

The paleogeographic evolution shows an important outbuilding of the slope facies along with shelf sediments dominated by carbonates on the eastern and southeastern margins of the basin, and a relative higher clastic supply from the southwest (Fig. 3 and 5). The accumulation of shelfal facies advanced toward the northwest together with a steepening of the slope and in the Early Valanginian. Within the *L. riveroi* ammonite zone (Fig. 2) an important downward shift took place with the accumulation of a series of sequences aerially restricted beneath the shelf break indicating the presence of a sequence boundary (136.0 Ma, approx.). In the western side of the basin, the new group of sequences is composed of shallow marine clastics (Fig. 7) to coarse-grained fluvial conglomerates known as Mulichinco Fm (Mitchum and Uliana, 1982; 1985; Gulisano et al., 1984). In the Malargüe area the lowstand event remained recorded within the shallow marine Chachao carbonates overlying the dark shales with a very sharp contact (Legarreta and Kozlowski, 1981). This Early Valanginian lowstand sequence-set laterally changes to basinal organic-rich shales (Fig. 2) but are not analyzed in this opportunity.

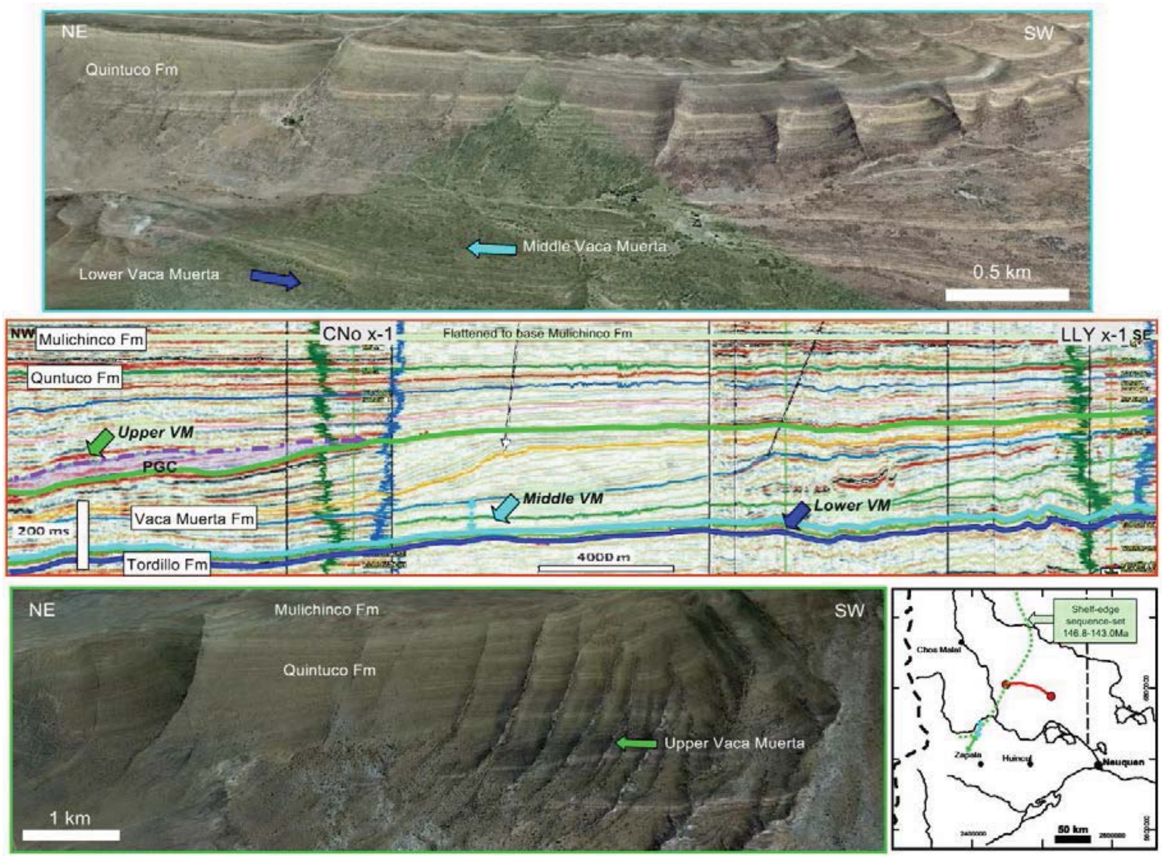

Figure 5. Upper and Lower: oblique view of the Sierra de la Vaca Muerta outcrops to see middle and upper Vaca Muerta sections and the progradational pattern (light blue and light lines in location map, respectively). Middle: 3D seismic line showing internal stratal pattern for the same intervals (modified from Pose et al. 2014); the lower Vaca Muerta shales are between the blue and light blue markers

Within the basinal to lower slope environment a new interval of organic-rich shales accumulated during the E. Berriasian to Early Valanginian, informally named in this study as upper Vaca Muerta. In many areas the base of this interval is recognized in well logs by a strong gamma ray kick, as occurs in the subsurface of Malargüe (Fig. 8). The distribution of this dark facies is restricted to the NW of Neuquén but widespread in the Malargüe domain, mostly developed along the fold belt (Fig. 1), displaying a thickness not higher than 100 m, according with the present-day data set (Fig. 5).

In the NW of Neuquén the three Vaca Muerta intervals are present in subsurface and in excellent outcrops where sequence-sets, sequences, systems tracts, parasequences (4^{th}-5^{th} order sequences), rock composition and paleontological data can be studied in detail (Fig. 6). In Malargüe fold belt area, many of this kind of high-quality outcrops are very close to exploration and development wells, in some cases less than 2 km, providing a good combination to analyze in subsurface these organic-rich facies.

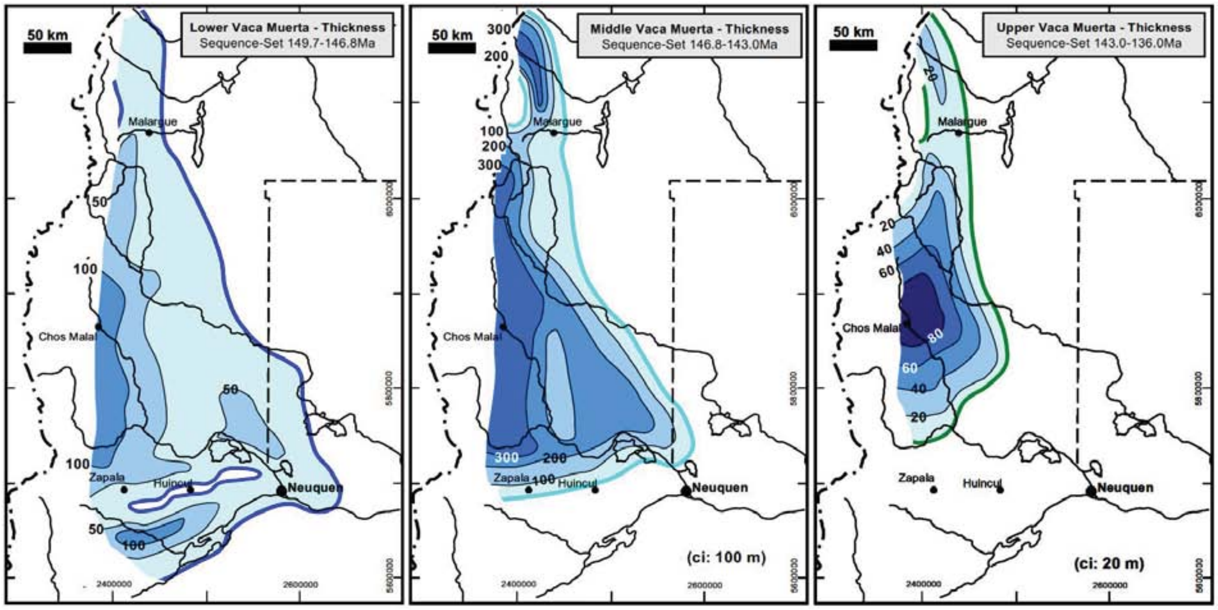

Figure 6. Thickness maps of the different Vaca Muerta intervals displaying a gentle NW migration according with the evolution of the sedimentary fill originally shown by Mitchum and Uliana (1982; 1985). Thickness heterogeneities are related to the presence of differently active internal highs illustrated in Figure 1.

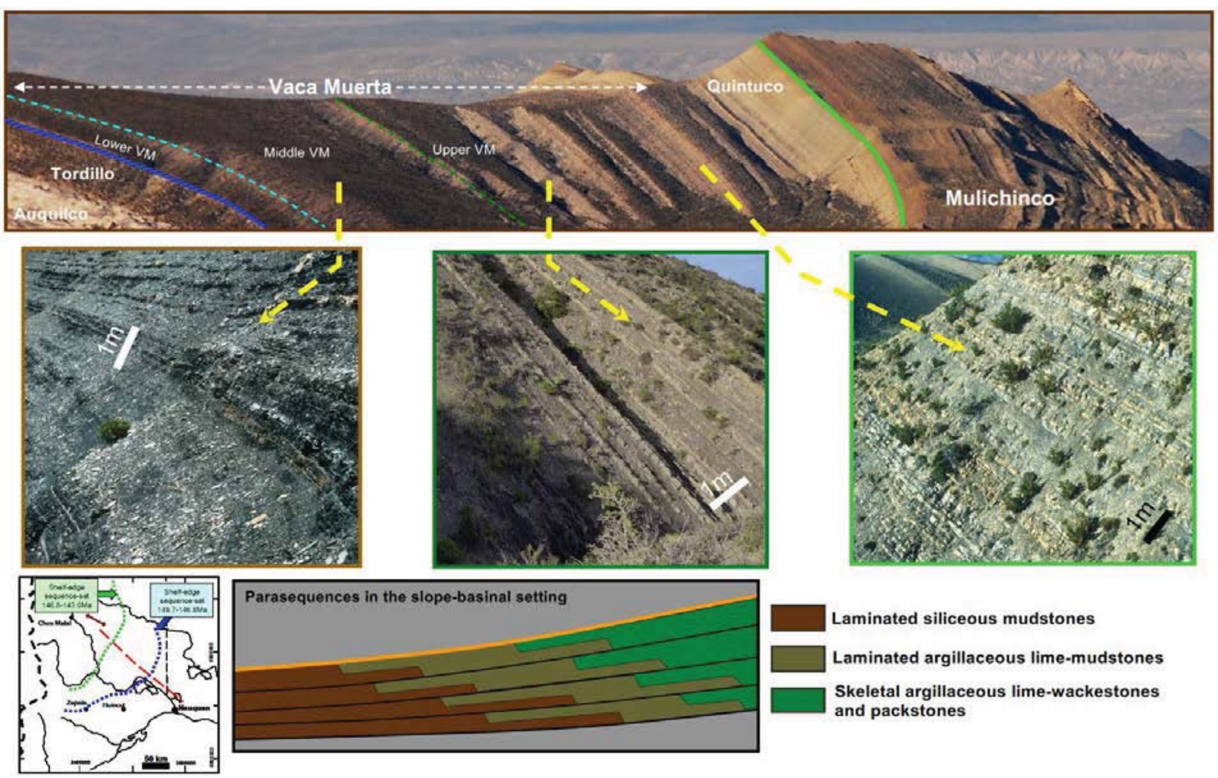

Figure 7. Outcrop in the NW of the Neuquén fold belt, where it is possible to study sequences, systems tracts, parasequences (4th or 5th order sequences), facies, and paleontological content. In this area the three "Vaca Muerta" intervals can be analyzed but display a high maturity level

Although the key facies in the basinal to slope environment are dominated by laminated siliceous mudstones, laminated argillaceous lime-mudstones and skeletal argillaceous lime wackestones and packstones (Fig. 6), the Vaca Muerta source rock displays variations depending on different sequence-sets, sequences and positions within the basin. Analysis of mineralogical composition shows different populations when plotted by area (Askenazi et al., 2013); however, within diverse areas Vaca Muerta can be composed of different chronostratigraphic units. In the SE corner of the basin the Early-Middle Tithonian (149.7-146.8 Ma) and the Upper Tithonian-Early Berriasian (146.8-143 Ma) intervals, informally named in this paper as "lower" and "middle" Vaca Muerta shales, respectively, show different composition (Repol et al. 2014). Presence and distribution of the Vaca Muerta intervals depend on the area under study. For that reason it is necessary to identify the time-equivalent interval (sequences) to perform an appropriate mineralogical composition analysis. The current and future drilling activities will provide a huge volume of data but they need to be analyzed within a sequence-stratigraphic framework, as illustrated by Pose et al. (2014) and González Tomassini, et al. (2014). Most the areas under exploration and development are covered by 3D seismic data good enough to tie to well information and generate detailed correlations of the key reservoir-bearing source rocks.

The Vaca Muerta Source Rock

Numerous publications through the last twenty years have described at different levels the geochemical characteristics of the Vaca Muerta shales and their associated hydrocarbon accumulations. The reader is referred to the following, non-extensive list of contributions that covers various aspects of the Vaca Muerta petroleum system: Villar et al. (1993), Urien and Zambrano (1994), Villar and Talukdar (1994), Wavrek et al. (1996), Legarreta et al. (1999), Uliana et al. (1999), Cruz et al. (1999, 2002), Legarreta et al. (2005), Villar et al. (2005); Rodriguez et al. (2007); Legarreta et al. (2008), Legarreta and Villar (2011, 2012), Boll et al. (2014); Borbolla et al. (2014); Elias et al. (2014), Sylwan (2014).

The black-to-brown bituminous marly shales of the Vaca Muerta Formation accumulated under strictly to moderately marine anoxic conditions that preserved elevated amounts of “high-quality”, hydrogen-rich kerogen. Organic petrography studies typically show a strong and monotonous predominance of unstructured organic matter thought to be derived from the anaerobic to dysaerobic early diagenesis of phytoplankton/algal-bacterial contribution. Alginite is sporadically recognized whereas participation of terrestrial relics, if any, is very scarce.

Organic contents usually span the range 3-8% of TOC, but can attain peaks of 10-12% or even higher, and are associated to S2-pyrolysis yields that mostly vary between ca. 10 and 50 mg HC/g rock, seldom reaching up to 90 mg HC/g rock, in mid to low-mature areas. Hydrogen Indices (HI) of representative low-mature Vaca Muerta specimens display values around 650 mg HC/g TOC, although in particular beds they can surpass 750 mg HC/g TOC; Oxygen Indices (OI) are typically below 30-40 mg CO_2/g TOC. Kerogen classification thus points to type I/II in the classical diagram of HI vs. OI.

The overall geochemical pattern of Vaca Muerta shales assigns an extraordinarily elevated oil-prone potential to the unit. Despite these characteristics, a mass balance approach by Legarreta et al. (2004; 2005) has documented a poor generation-accumulation efficiency for the Vaca Muerta petroleum system in regard to conventional resources at a basin scale. Lack of adequate timing of source rock maturation and trap availability was invoked by the authors to justify the unpararelled data of limited oil accumulation in conventional reservoirs and the immense amount of hydrocarbons proved to have been generated and not trapped by the Vaca Muerta shales. In addition, quoted lines of the 2004 paper state “*Geological data obtained from exploration wells indicate the presence of an important volume of oil retained/accumulated (?) within the Vaca Muerta basal section (Late Jurassic source rock). Up to now, few wells have had non-commercial production from that overpressured interval in the Neuquén embayment, but these observations provide encouragement to the testing of a new play*”. This hypothesis seems to have been proved years later when numerous wells found highly qualified oil resources within the Vaca Muerta source rock. In fact, detail pyrolysis studies performed on key wells through the basin confirmed very abundant presence of “free hydrocarbons” expressed by elevated S1 responses, possibly due to defective expulsion capacity. In particular, Vaca Muerta sections with thermal maturities in the peak to late oil generation phase typically show OSI (Oil Saturation Index, S1x100/TOC) values that largely exceed 100 mg/g, implying enhanced production potentiality (Jarvie, 2012) for unconventional oil.

Representative logs of TOC and HI in three selected positions of the basin are depicted in Fig. 8 for the Vaca Muerta sequence-sets defined in Fig. 2, covering the Picún Leufú depocenter, the Embayment Area, which involves the most important oil districts, and the Malargüe Area.

- The lower Vaca Muerta, developed during the accumulation of the oldest sequence-set (149.7-146.8 Ma), contains an important participation of radioactive elements which has a strong effect in the gamma ray logs. Also, a noticeable feature is the log response with high resistivity and an important sonic velocity decrease. This interval is very characteristics in logs (Veiga and Orchuela, 1988) and several examples have been recently published (Stinco and Barredo, 2014). At the Picún Leufú Area, Vaca Muerta kerogen varies to II-S (sulfur-rich) type, deposited in an euxinic paleoenvironment (Wavrek et. al., 1996; Legarreta et al., 1999; Cruz et al., 1999).
- The middle Vaca Muerta accumulated within the youngest group of sequences (146.8-143 Ma) of the first 2nd order cycle (149.7-143 Ma). In the Neuquén Embayment and in internal positions of the basin, the lower Vaca Muerta is relatively thin and displays a gradual decrease of the TOC content along with the increase of the maturity level. On the contrary, this middle interval shows more variable vertical values (Fig. 8), mostly related to the presence of shales accumulated during the transgressive and highstand systems tracts. Individual thickness of the richest sections depends on the position within the sequence-set and the area analyzed.

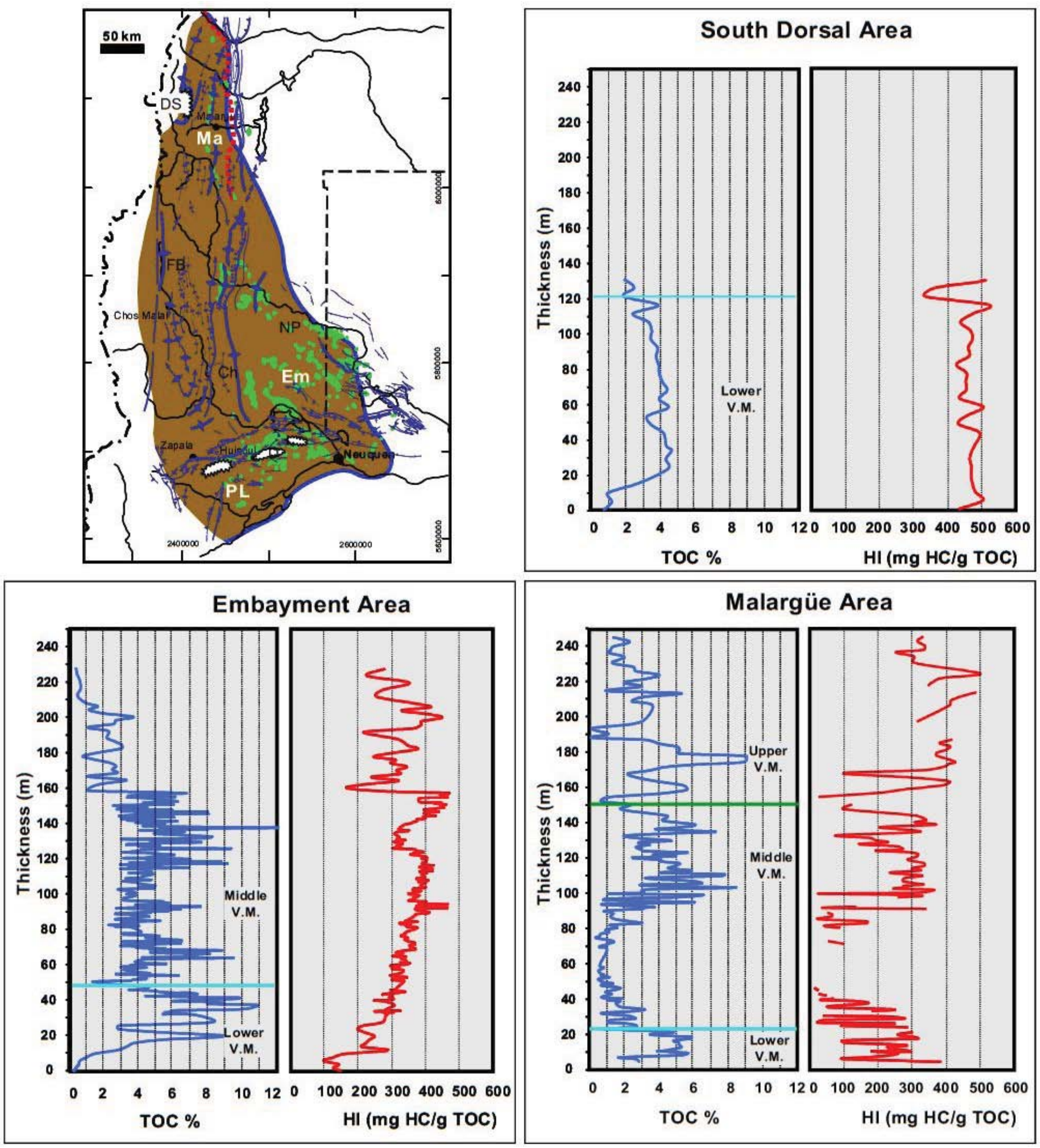

Figure 8. Plots displaying Thickness (m) vs. TOC (%) and HI (mg HC/g TOC) to illustrate the geographical and stratigraphic variations within the different intervals of Vaca Muerta source rock (Fig. 2). Location of the areas Ma=Malargüe; Em-Embayment; PL=Picún Leufú

The upper Vaca Muerta developed within the Early Berriasian-Early Valanginian sequence-set (143.0-136.0 Ma) is mostly present in NW Neuquén and in the Malargüe Area. Available data are far fewer than those of other intervals. However, it is interesting to highlight the good TOC content in the Malargüe domain, not only in the lower and middle sections but also in the upper one.

Thermal Maturity

The present day regional thermal maturity of the Vaca Muerta Fm in terms of vitrinite reflectance is shown in Fig. 9 at a basin scale referred to the level of lower Vaca Muerta interval. The map, modified from Legarreta and Villar (2011), highlights the core areas for gas, gas-condensate and oil. The crossplot of depth vs. Ro% details bulk maturity trends for comparison purposes of several key areas. A detail approach of the evolution of the transformation ratio of the source rock trough time can be found in Legarreta et al. (2004; 2005).

- The Malargüe (Ma), Northeast Embayment (NE) and Picún Leufú (PL) areas display stages of immaturity/early maturity to mid-maturity for oil at very different depth ranges. In particular, Vaca Muerta at PL shows sufficient maturity for initial conversion to early oil (favored by kerogen type II-S) at rather shallow depths around 1500 m. At the location of La Hoya x-1 well, Santiago et al. (2014) have recently documented mid to incipiently late maturity at around 1800 m, associated to the occurrence of light oil, which is fairly uncommon for this part of the basin. The NE pattern involves early to mid oil window maturities (Villar el al., 1993) that extend over a broad depth interval of ~2200-3200 m. The Ma maturity trend and related area to the north (Boll et al. 2014), display an intermediate pattern regarding the oil window depth when compared to NE and PL.
- In the Northwest Neuquén (NN) area the thermal maturity spans a wide range from mid maturity to advanced gas-condensate stage, involving depths from ~2000 m to 4000 m. Data for the El Trapial Field has been recently published by Fantin and González (2014).

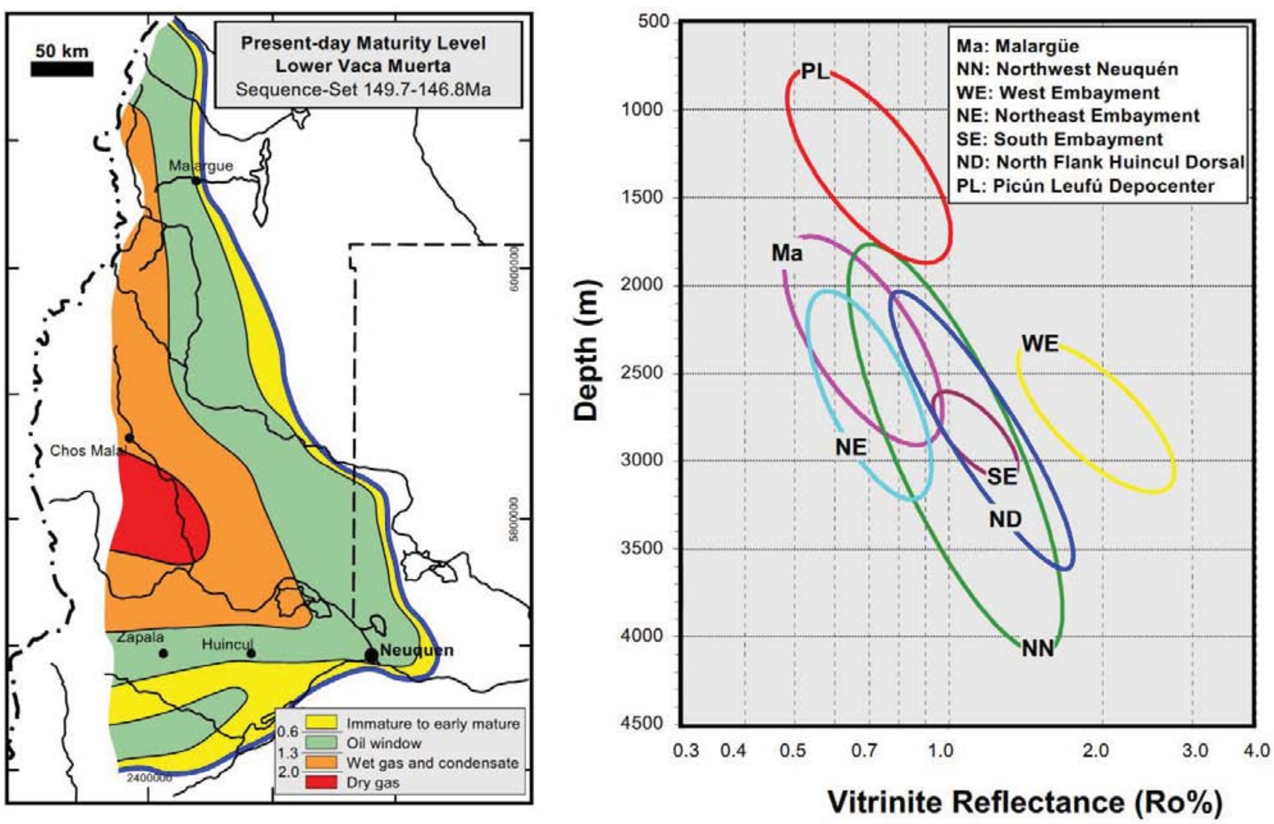

Figure 9. Left: Present-day maturation level, mostly referred to the lower Vaca Muerta section. Right: Plots displaying Depth (m) vs. Vitrinite Reflectance (Ro %) obtained for different key areas

- The North Flank of Huincul Dorsal (ND) involves mid- to late-oil and advanced gas-condensate stages in the depth interval ~2500-3600 m.
- The area of the West Embayment (WE) is characterized by an overall high thermal maturity that covers the gas condensate and dry gas stages in the depth interval ~2300-3200 m.

Vaca Muerta Oils

Oils throughout the basin display significant variations that reflect not only the different thermal maturity trends of the source rock but also changes in the generating organic facies (Villar et al., 1993; Wavrek et al., 1996; Villar et al., 1998; Cruz et al., 1999; Legarreta et al., 1999; Villar et al., 2005; Legarreta et al., 2012). Representative gas chromatography and biomarker fingerprints are shown in Fig. 10 for oils of the Picún Leufú, Embayment and Malargüe Areas. The diagrams highlight several key features for comparison among the oils.

- Malargüe oils show a mixed shaly-carbonate pattern. Diagnostic features for this carbonate-enriched source include pristane much lower than phytane (Pr/Ph ratio ~0.7-0.9), comparatively high presence of C_{29} norhopane in the hopanes distribution, and relatively low amounts of diasteranes compared to regular steranes.
- Embayment oils are characterized by an essentially siliciclastic source pattern. Pristane is equal to or slightly higher than phytane (Pr/Ph ratio~1.0-1.2), C_{29} norhopane is much lower than C_{30} hopane, homohopanes show a continuous decreasing concentration from C_{31} to C_{35}, and diasteranes are much higher than steranes. These features gradually change towards the northeast platform, where Vaca Muerta sourced oils denote a carbonate-enriched organic facies.
- Picún Leufú oils, sourced by sulfur-rich kerogens accumulated under restricted euxinic conditions, typically portray very low pristane with respect to phytane (Pr/Ph ratio ~0.5-0.8), together with high presence of the C_{35} member in the distribution of C_{31}-C_{35} homohopanes, in a general context of early to mid thermal maturity level. The mentioned publication of Santiago et al. (2014) that documented a light and advanced-mature Vaca Muerta oil at La Hoya seems to be an exception to this typing.

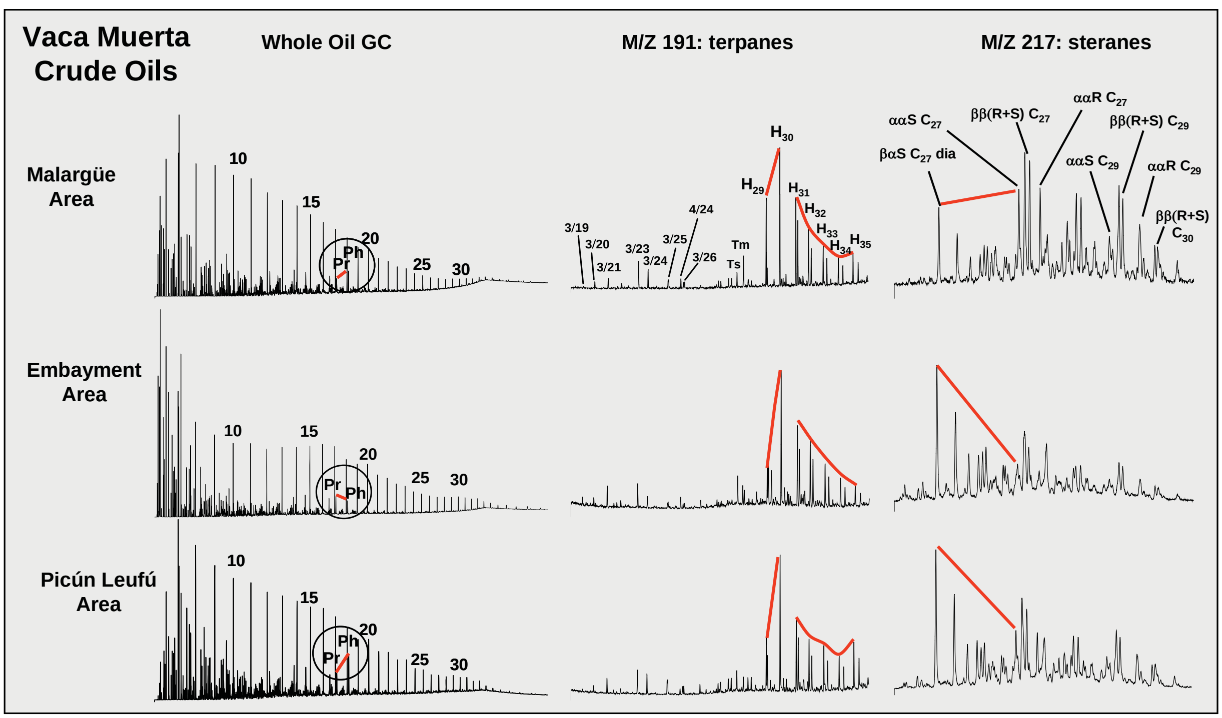

Figure 10. Gas Chromatography (GC) and biomarker fingerprints (M/Z 191 and M/Z 217) of three representative Vaca Muerta sourced oils in the Malargüe, Embayment and Picún Leufú areas (see Figure 1 for location of the areas). The labels 10, 15, 20, 25, 30 in the GC traces indicate carbon number of n-alkanes; Pr: pristane; Ph: phytane; 3/19, 3/20, 3/21, 3/23, 3/24, 3/25, 3/26 refer to tricyclic terpanes of 19, 20, 21, 23, 24, 25 and 26 carbon atoms, respectively; 4/24: tetracyclic terpane C_{24}; Ts: 18α(H)-trisnorhopane; Tm: 17α(H)-trisnorhopane; H_{29}: C_{29} 17α(H)21β(H)-norhopane; H_{30}: C_{30} 17α(H)-hopane; H_{31} to H_{35}: C_{31} to C_{35} 22S and 22R 17α(H) hopanes; βαS, ααR, ααS y ββ(R+S) refer to C_{27}, C_{29} and C_{30} sterane isomers; dia: diasterane. The red lines/curves highlight key features for comparison of the oil types: Pristane/Phytane ratio, H_{29}/H_{30} ratio; relative abundance of diasteranes with respect to regular steranes, distribution of C_{31}-C_{35} homohopanes

Conclusions

The understanding of the geological and geochemical composition and variations for each Vaca Muerta section is crucial to explore and develop the unconventional reservoirs.

From the geochemical point of view, the available public domain data, allows to visualized key changes within the lower Vaca Muerta, Early to Middle Tithonian (149.7-148.6 Ma); however, for the middle unit, Upper Tithonian-Early Berriasian (146.8-143.0 Ma), and the upper Vaca Muerta, Early Berriasian-Early Valanginian (143.0-136.0 Ma), data is not enough to perform a similar analysis.

From the geological point of view, the mineralogical composition needs to be analyzed within a same stratigraphic level in different areas of the basin.

The current and future drilling activities will provide a huge volume of data which needs to be analyzed within a sequence-stratigraphic framework. Most of the areas under exploration and development are covered by 3D seismic data good enough to tie to well information and generate detailed correlations of the key reservoir-bearing source rocks.

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