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Unconventional Shale Pore System Characterization in El Trapial Area, Vaca Muerta, Argentina

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Summary

Located in the Argentinean Neuquén Basin, the Vaca Muerta formation is a thick succession of Late Jurassic-Early Cretaceous organic rich siliceous marlstones and mudstones with clay content below 30%. It is the main source rock of the reservoirs in the basin that have been producing since 1918. The El Trapial area is situated in the North West part of the basin. The Vaca Muerta formation is encountered at burial depth ranging from 2000–4200 m, and it extends over various thermal maturity windows in the study area from early oil to wet gas maturity windows. The organic-rich interval has a thickness of around 350 meters, with total organic carbon ("TOC") ranging between 2 to 8% and average total porosity of 10%. Following the local maturity trends, hydrocarbon type has been found to vary laterally and presumably vertically. The maturity variations in the El Trapial area poses the challenge of understanding productivity drivers in the peak oil, late oil and gas condensate windows, with each maturity type potentially responding to different factors.

A field study was initiated in 2011, analyzing resources with the available information (five wells with vintage logging suites and 80 percent of 3D seismic coverage), and then continued with a drilling campaign of four vertical exploratory wells with an aggressive data acquisition program. Full wireline log suites were run in the exploratory wells and more than 400 m of core was acquired. Laboratory studies were performed on conventional core, sidewall cores and cuttings samples to characterize the reservoir properties and to calibrate petrophysical and geomechanical models.

Among the various petrophysical challenges offered by Vaca Muerta, the characterization of the porosity system is critical to understand the reservoir quality. Only considering the organic and inorganic pore systems brings into play many more questions regarding their respective contributions to oil production, in the early and late stages, and their relationship with potential formation water production. The NMR T2 distribution combined with laboratory data is the key to assess a better understanding of the pore system.

The present work defines a new effective pore model for the El Trapial area to interpret the NMR T2D. The study relies on an extensive core measurement database and enables a improve prediction of the better productive zones in Vaca Muerta.

Introduction

Vaca Muerta formation is believed to exhibit at least three types of pores, the clay intra-particular pores containing the clay bound water (CBW), the inorganic matrix-hosted pores (IP phi), including inter-particle and intra-particle porosity and the organic matter-hosted pores (OM phi). As Loucks (2012) mentioned, the pore system varies in depth and is affected by several processes. Compaction can decrease the IP phi volume with increasing burial depth; on the other hand, dissolution of instable chemical particles can create additional moldic porosity and abnormal pore pressure can reduce the effect of compaction. The OM pore distribution, created in kerogen within the hydrocarbon thermal maturation window, can vary depending on OM type (Loucks 2012). Kuila et al (2014) demonstrate that there is a clear correlation between pore structure and the thermal maturity of organic rich shales in the range of micro and fine mesopores. Bohacs et al (2013) suggest that OM phi can be a function of the type of organic matter and its original hydrocarbon content, and Alcantar-Lopez and Chipera (2013) suggest a colloidal system and conclude that OM pore size, shape and distribution are the result of the organic nanoparticle distribution within the inter-crystalline spaces as well as the events that may have occurred (migration, compaction, organic degradation, etc.). In conclusion, the OM pore system is a complex system which may be driven by general principles, but with high local variability.

Due to the very distinctive NMR signal of the pores hosted in clay minerals, in this study they are presented and analyzed separately from the other pores hosted in the inorganic matrix. Figure 1 summarizes the Matrix-Pore-Fluid model assumed for this analysis.

Figure 1—Schematic Matrix-Pore-Fluid model for Vaca Muerta

In shale oil, initial production is mainly determined by the hydraulic fracture surface area, the volume of moveable hydrocarbons and the pore pressure, but subsequent production depends also on factors such as the matrix permeability. As a result, it becomes a key to understand how the bigger and well connected pores are distributed (Rylander et al., 2013). It is also reasonable to think that liquid hydrocarbons with different densities fill the OM and IP pores, and hence each will contribute at a different time to the production. A detailed characterization of the pore system is critical to distinguish the presence of OM phi and IP phi and their vertical and lateral variations along the area to be developed.

Oil plays present an extra challenge in comparison with shale gas plays, due to the presence of bigger molecules and higher viscosity fluids. A minimum pore throat is necessary for oil molecules to move through the shale pores (Bohacs et al, 2014; Rylander et al, 2013; Nelson, 2010; Nelson, 2009).

The maturity window of the exploratory wells in the study area range from early oil to wet gas/condensate windows. Oil studies indicate that the oil produced in the region is rich in saturated hydrocarbons and presents very little proportion of asphaltenes (Villar, 2014). Base on Jarvie (2008) these hydrocarbon molecules would be smaller than 3–5 nm. Pore throats diameters measured with mercury injection (MICP) indicate sizes on the range of 4–30 nm and scanning electron microscope images reveal pore sizes two to four orders of magnitude above oil molecule size (Figure 2). Figure 3 shows the pore, pore throats and molecule sizes for the studied area. It follows that the pore system characterization is relevant for the Vaca Muerta shale oil evaluation.

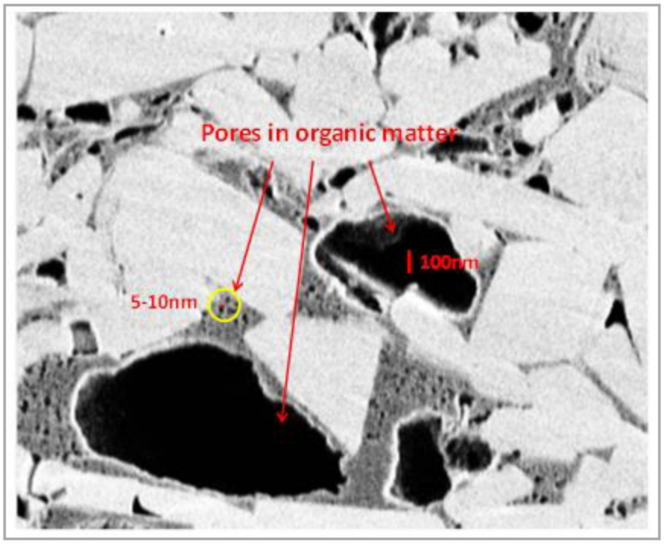


Figure 2—SEM image showing OM phi pores range of sizes.

Diameter (nm)	
0.38	Methane Molecule
0.38-3	Oil molecule
4-30	Pore Throat
2-1000	OM phi
20-1000	IP phi

Figure 3—Pore, pore throat and fluid molecules size for the studied area

Methods for Characterizing Vaca Muerta Pore System

This work investigates pore size distribution within the Vaca Muerta formation, based on a comprehensive evaluation of the NMR log and several laboratory studies applied in cores and sidewall cores.

Mercury Injection Capillary Pressure (MICP)

Mercury is progressively injected into the rock sample at increasing pressure steps up to 60,000psi. The size of the connected **pore throats** is calculated from Hg volume (Figure 4). This laboratory technique can measure pore throat diameters bigger than 3.6 nm.

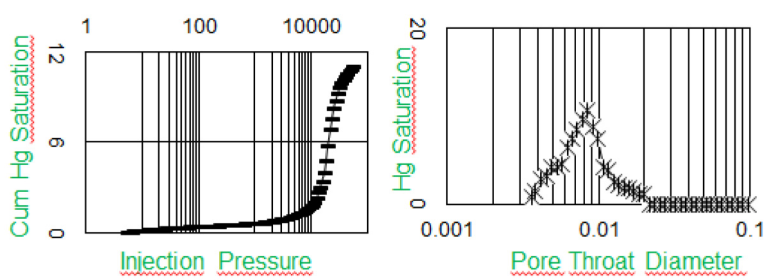


Figure 4—MICP examples showing, on the left the increment in Hg volume injected in the sample with increasing pressure. On the right the Hg volume is converted to pore- throat size.

Scanning Electron Microscope (SEM)

SEM data is considered to be critical to understand a shale pore system due to the fact that it's the only technique that allows visualizing directly where the porosity is hosted (pores in the organic matter or the inorganic matrix), its type (intergranular, intercrystalline, intergranular, etc), size and shape. Taking into account the very detailed scale of observation, many samples should be done before assuming representativeness of the interpretation for a certain interval.

Among the SEM types, the Ion beam milling method emphasizes material density allowing an easy identification of pores, kerogen and grains (Figure 5). This technique allows distinguishing pores bigger than 5nm.

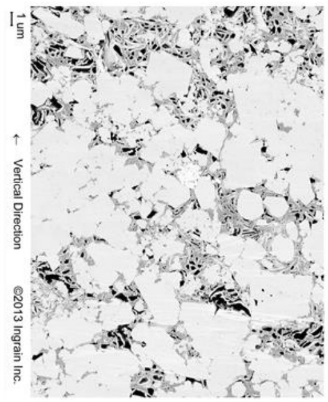


Figure 5—Ion milled SEM where inorganic material (clays, carbonate and quartz) shows up light gray, organic matter is darker gray and the pores black.

Processing several 2D SEM images, a 3D FIB-SEM volume can be obtained. The advantage of these volumes lies on the understanding of the connectivity of pores within a sample. Organic matter and porosity can be calculated for each volume. Additionally, a quantification of OM phi and IP phi can be obtained (Figure 6).

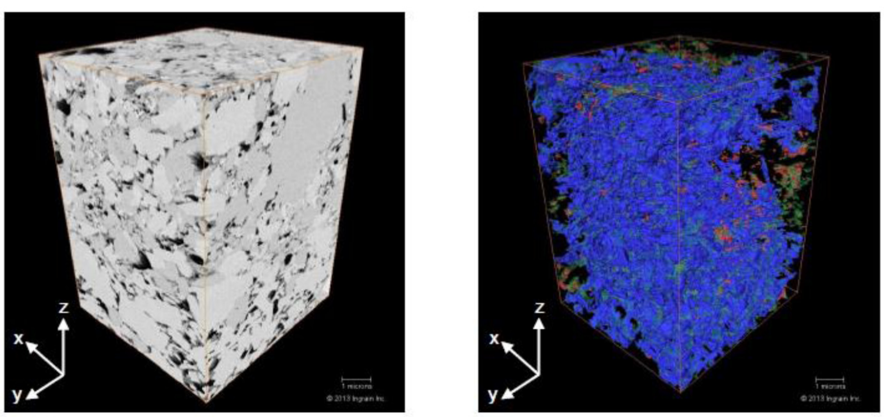


Figure 6—On the left 3D FIB-SEM where white sections corresponds to high density materials, light grey minerals with densities around 2–3gr/cc, dark grey represents the organic matter and black is pore space. On the right a 3D FIB-SEM where organic material is represented in green color, connected porosity in blue and non-connected porosity in red.

Subcritical Nitrogen Gas Adsorption (SGA)

In this laboratory technique Nitrogen at 77.3K is intruded into the sample and the pressure and gas quantity are recorded as isotherms (Kuila et al, 2014; Saidian eta al, 2014; Kuila et al, 2012). These isotherms are the base for calculating the connected pore size distribution (Figure 7). SGA can measure pores from to 2nm turning it in a powerful study for shale analysis where there is a significant amount of very small pores. Unfortunately the technique is not able to measure volumes contained in pores bigger than 200nm giving a limited range of measurement.

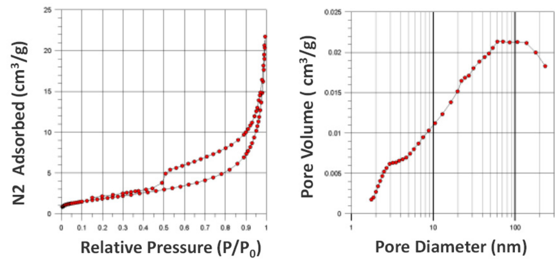


Figure 7—SGA Isotherms and Pore Size Distribution on the same sample

A SGA study can be complemented by repeating the measurement in the sample after the organic matter has been removed using NaOCl as a solvent (Kuila et al, 2014). By comparing results before and after organic matter removal valuable information on OM phi presence and amount can be obtained. Figure 8 shows two examples from Vaca Muerta pore size distribution (PSD). On the left, Figure 8A, the analysis shows no significant variation of pore volume with less than 20nm diameter, potentially indicating the absence of significant OM phi, at least in the 2–200 nm range of the technique (SEM from a close sample shows predominance of IM phi). The behavior of the curves is different in pore sizes bigger than 20nm where the increment of pore volume after solvent treatment points out the presence of solid, no porous organic matter patches.

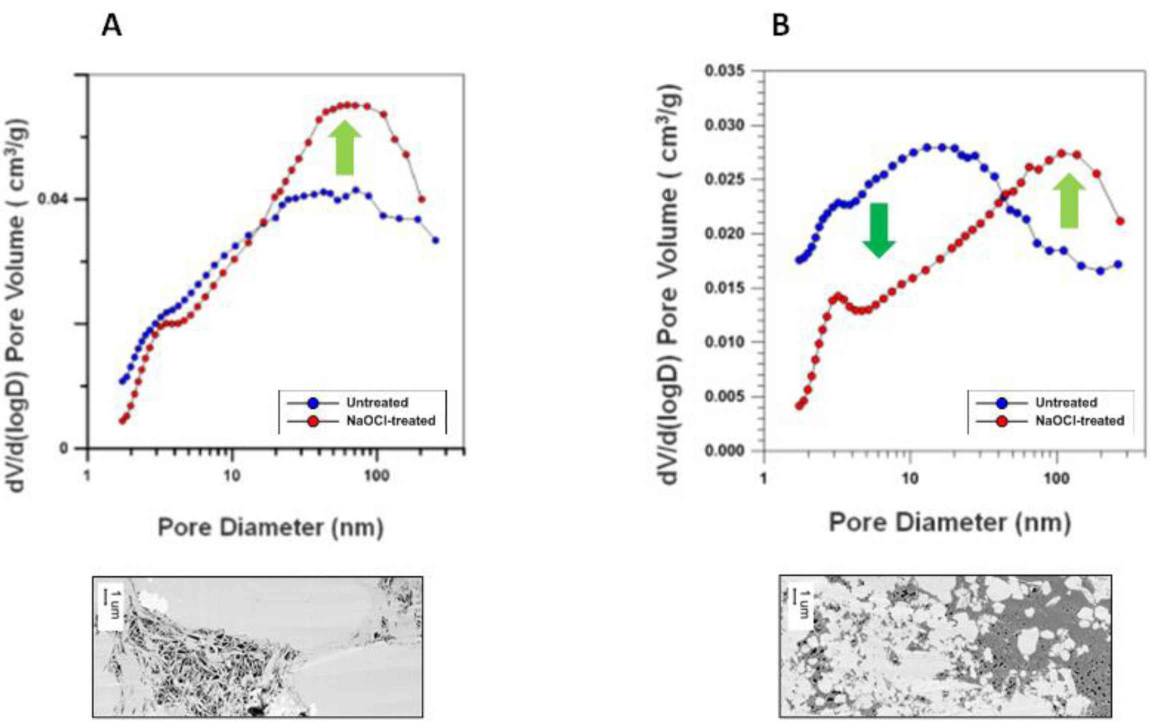


Figure 8—Examples of Vaca Muerta SGA and SEM. Blue curve corresponds to PSD in the untreated samples while red curve represents the PSD in the samples after removing the organic matter. On the left an example of scarce OM phi sample and, on the right an example of significant presence of OM phi sample among the 2–50 nm within Vaca Muerta.

On the right, in Figure 8B, the treated sample presents a pore volume reduction of pores smaller than 40nm; this is indicating the presence of small pores hosted within the organic matter (Note OM phi in SEM). On the contrary, the increment of bigger pores due to organic matter removal suggests OM packs were present in a continuous size typically larger than 40 to 50nm..

Nuclear Magnetic Resonance in El Trapial wells

NMR Acquisition Parameters

The Nuclear Magnetic Resonance logs were recorded with a tool that benefits from 0.2ms echo spacing, a single ~1.15in depth of investigation and a robust signal-to-noise ratio (McKeon 1999). The acquisition sequence was optimized for shale logging with enhanced precision mode (Hook 2011). The activation consists of a main sequence with 2.09s wait time and a record of 1800 echos at 0.2ms fixed echo spacing, complemented by 50 repetitions of a sub-sequence with 20ms wait time and a record of 30 echoes at 0.2ms. The logging speed for this activation sequence is 600ft/h. It is important to note that due to the tool design, the effective polarization time (about 6s), including pre-polarization and wait time, is much longer than the single 2s wait time.

Produced oil API measured in El Trapial ranges from 44 to 54 °API, with GOR from 1400 to 5400 scf/stb. Expected downhole (~120–140degC) bulk oil T1 and T2 relaxation times are in the “second” range. The observed T2 distributions in Vaca Muerta in El Trapial show a signal that is typically limited 300ms and less. Potential high T1/T2 component such as bitumen and heavy ends are limited to short T2. As a result, an effective 6s polarization time is expected to fully polarize formation fluids.

Inversion method and Considerations

Time echo inversion was done by Chevron Energy Technology Company (ETC) in order to optimize the dynamic of the estimated T2 distribution, and limit the impact of the regularization in the distribution. The T2 min and max of the estimated distributions are respectively 0.1ms and 1000ms. An in-house logic ensures the robustness of the low T2 extrapolation, but it is clear than no real information lies in the first bin up to 0.3–0.4ms.

In this contribution, the T2 distribution will be mainly interpreted in term of pore size distribution and formation fluid properties. This implies that these properties are the main drivers for the downhole T2 distribution. Two other factors that can affect the T2 distribution are invasion and presence of iron. The wells were drilled with Oil-Base-Mud (OBM). The absence of moveable water under drilling conditions is controlled by shallow to deep resistivity logs comparison. Oil filtrate invasion removing formation oil could potentially occur, as oil filtrate has been reported near the center of full cores. However, it is assumed that the effect of a limited amount of dead-oil filtrate will not perturb significantly the T2 distribution. Typical mineralogy of Vaca Muerta formation in El Trapial area does not show significant amount of iron-bearing minerals (chlorite or siderite) except from the pyrite associated to the Kerogen (Figure 9). As organic matter pore system is one of the variables under consideration for this study, we will assume that the pyrite effect is lumped into the OM pore relaxivity term.

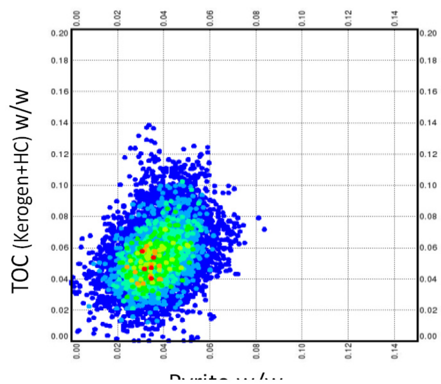


Figure 9—shows the relation between TOC and pyrite content, being TOC 3 vol% maximum for the studied area.

While some consideration about bitumen effect will be devised, the presence and quantification of bitumen contribution is beyond the scope of this contribution. Bitumen T1 in laboratory condition has been reported to be in the 0.1ms range with a high T1/T2 ratio (Kausik 2014). Using a 0.2ms TE tool, part of the bitumen will be included in the short T2 distribution, but with unknown proportion at this stage.

NMR response simulation

Before proceeding to the actual observation of the NMR T2 distribution, it is important to illustrate some of the limitations of the log-derived T2 distributions. Indeed, the separation of different contribution due to different fluids in different pore types is not always granted. It imposes taking some caution before pushing too far the T2 distribution interpretation. Three different situations were simulated using the actual activation sequence and typical tool noise. The first simulation represents a pure 2p.u. clay bound water formation, with 0.8ms T2. The second simulation adds two contributions, here called organic matter oil with 3ms and inorganic porosity oil with 30ms. The last simulation presents the same fluids, but with slightly larger OM pores distribution together with tighter IP pores. The results of simulated logs are displayed in Figure 10. The first observation is that the clay bound water signal that was clear in shale is apparently absent from the two other formation responses, even if present in the model. The second is that two oil pics are separable in the second simulation, while they appear together, as a single contribution in the last simulation that however is not that different in term of respective OM and IP positions. These results illustrate, if need has been, that T2 distribution interpretation should be handled with care in mudstone.

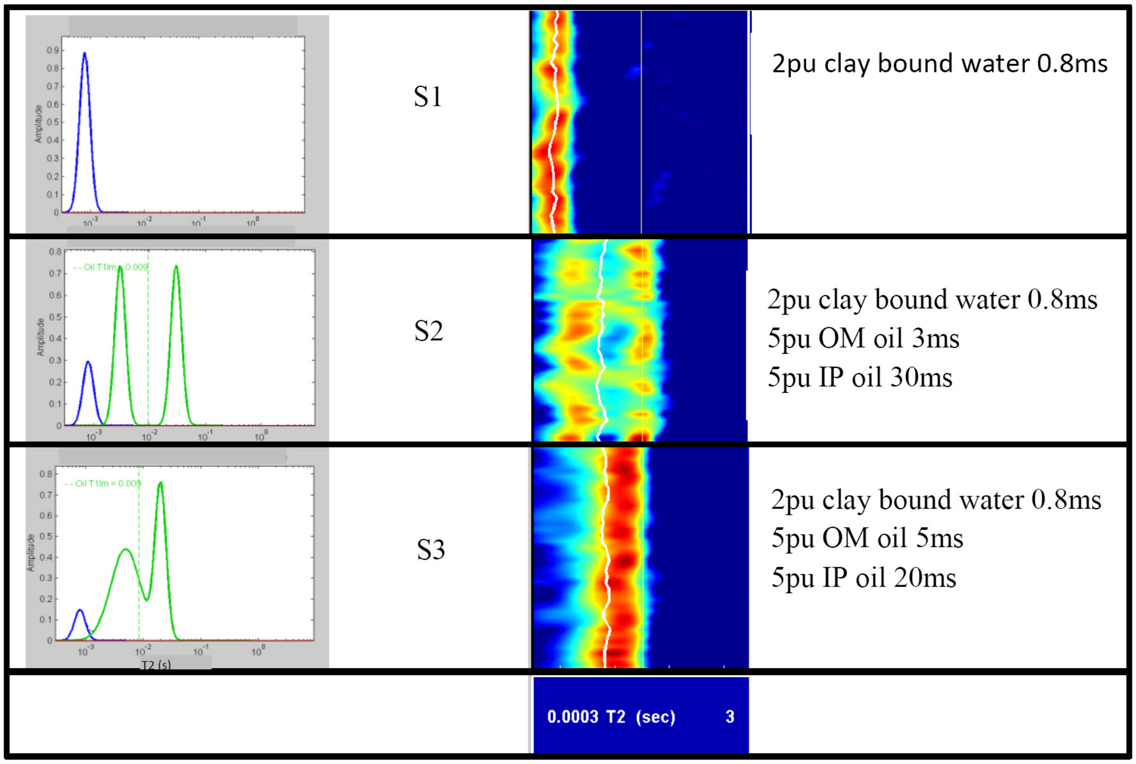


Figure 10—Simulations of NMR repsonses to 3 different pore distribution models. The separation of the individual contributions is not always granted. An apparent unimodal distribtion can hide a true bimodal underlying system, due to inherent measurment inversion limitations.

Preliminary Observation from Large Scale Trends to Local Factors

The NMR T2 distribution in all Vaca Muerta wells in El Trapial field present typical and consistent patterns. Figure 11 presents the T2 distributions of four wells (A, B, C and D in columns 3 to 6 respectively).

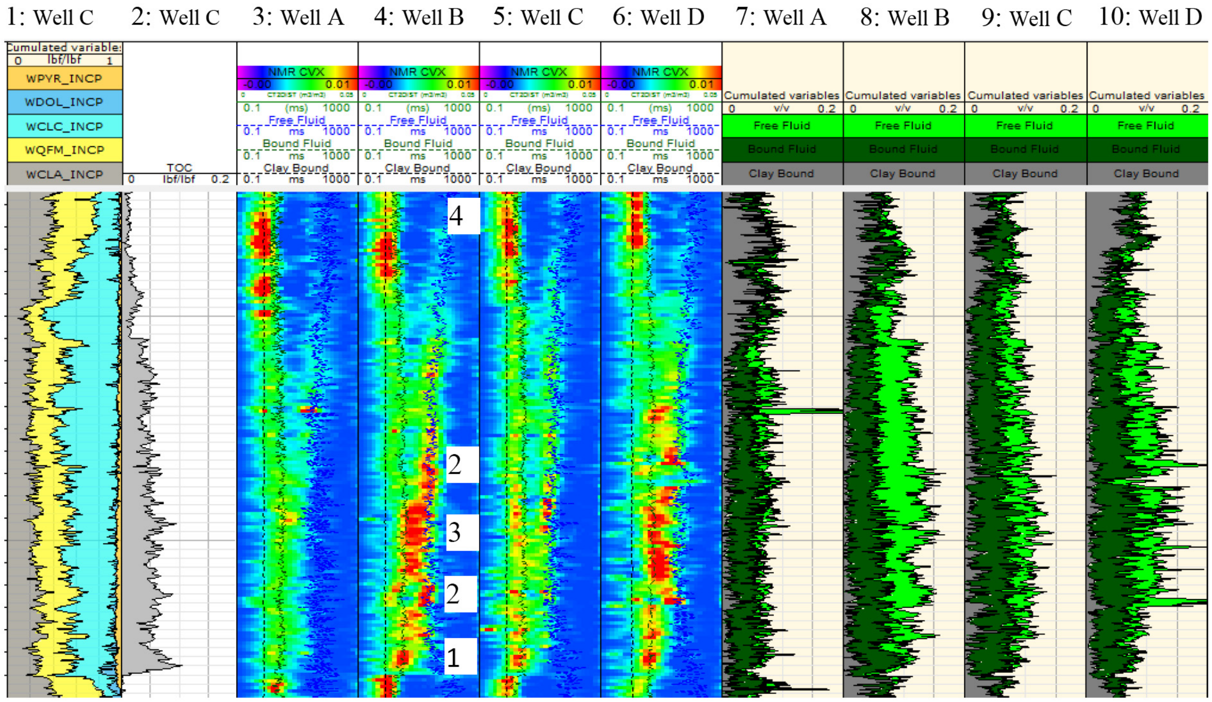


Figure 11—Observation of general trends in the T2 distributions in the study area. Wells are depth match at the base of Vaca Muerta. Columns 1 (lithology) and 2 (downhole TOC) are associated to well C (column 5) and are presented to give the general context Volumes of the three amin gaussian contribution to the distributiosna re reported on the 4 plots on the right hand side. The thick vertical depth division marks each 250m. The description of the curves can be found in the text.

The patterns can be grossly separated into four T2 types. The base of Vaca Muerta is characterized by an apparent unimodal T2 distribution located below 10msec (type 1 in Figure 11). Moving upwards, the distribution gradually divides into two modes with the longest mode being higher than 10msec (type 2 in Figure 11). Some intervals show again an apparent unimodal distribution, with a higher T2 than the bottom type (type 3 in Figure 11). Finally, the organic-matter-lean facies from the upper Vaca Muerta section are represented by a main unimodal T2 distribution located below 3msec, associated with a sparse and weak longer T2 contribution (type 4 in Figure 11).

A CIPHER processing was done on each of these well to enlighten and quantify the general trends. CIPHER relies on a new time domain inversion method (Clerke 2014). It is based on a petrophysical restricted stochastic search of three Gaussian components forming T2 distribution directly in the space of pulse decay curves vs. time. This method was developed for carbonate reservoir characterization, but it finds a new application here in unconventional mudstone reservoirs characterization. It provides a good grasp on the variability and global-scale features of the T2 distribution and allows a first quantification of the volumes of clay bound water, bound and free fluid.

In Columns 3 to 6, the T2 of each main Gaussian are presented in dashed curves. “Clay Bound” is constrained to remain on clay bound water and is calibrated in the upper shale (black color). “Free Fluid” is the upper Gaussian that lies above 10ms (blue color); it could be associated with inorganic porosity, as it is present in om-lean sections. It shows a global shortening trend as the depth increases, potentially due to compaction effect, convoluted with pore pressure variations. “Bound Fluid” lies in-between (dark green color); this contribution could be associated with organic porosity and a part of non-clay bound water. The volumes associated to each Gaussian are reported in Columns 7 to 10. “Clay Bound” Gaussian volume is color-coded in grey, as it mainly represents the clay bound water, plus a potential small contribution from bitumen. “Bound Fluid” Gaussian is color-coded in dark green and “Free Fluid” is color-coded in light green. It can be seen that each well has a distinct volume signature, despite sharing the same apparent global vertical features.

In general terms, these patterns can be interpreted as follow (going downwards, from top to bottom). In the marls with high clay content, the porosity is mainly due to clay bound water, and the T2 distribution is principally unimodal (type 4, and simulation S1 in Figure 10). As soon as the clay content decreases and in conjunction with an increase of organic matter, the low part of the distribution shift to the right. At the same time, the contribution of a larger pore system probably associated with inorganic porosity increases. It results in a distribution of type 2 (simulation S2 in Figure 10). Depending on factors that will be studied below, the distribution then balances between unimodal and bimodal (S3 and S2). It probably indicates that the organic porosity benefits from a larger pore size distribution, becoming broader and shifting right, and at the same time that the inorganic porosity has a reduced-size pore distribution. Variation of the fluid properties could also impact the T2 distribution, though it may not be the leading factor.

A model of the general trend can be derived from the observations above and it is illustrated in Figure 12. This model does not account for the local formation variations, and cannot be predictive of the details of the T2 distribution. Real T2 distributions show much more complex and dynamic figures. The objective of the following sections in this contribution is to better understand and characterize the local variations of the T2 distribution, in relation with the pore type distribution. For that purpose, local knowledge and lab measurements on cores will be used to better delineate the relevant factor affecting the NMR T2 distribution and doing so, to improve the understanding of Vaca-Muerta pore structure.

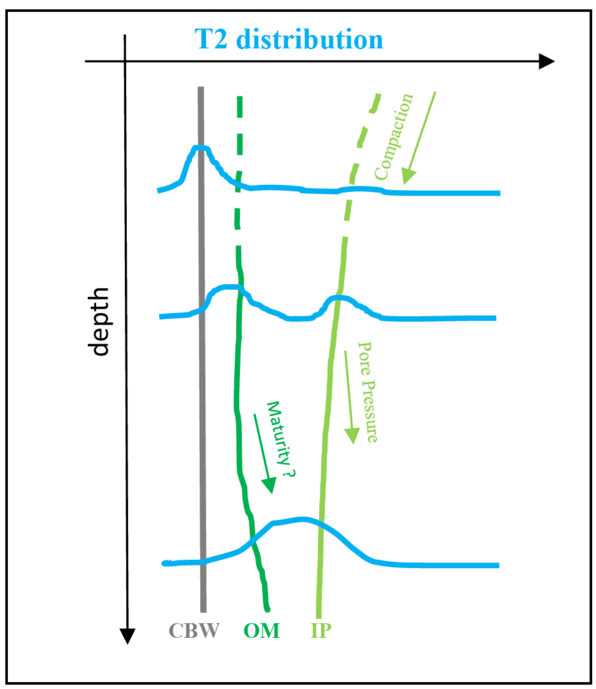


Figure 12—Sketch of large scale factors driving the NMR T2 distribution

Thermal Maturity Control

As discussed in the introduction, there is no simple model to predict the effect of thermal maturity on the organic matter pore system. Many publications have reported studies on organic matter porosity and its relation to thermal maturity (Loucks 2012, Kuila et al 2014). This factor is critical in the creation of kerogen pores. Kuila et al (2014) defined that the presence of micropores and fine mesopores within the

OM itself are only observed in thermally mature samples where the RockEval Hydrogen Index (HI) is <100. In the El Trapial area it was found that OM phi is recognized from the late oil window, where Ro is higher than 0.9% and RockEval Hydrogen Index (HI) is <150 (Figure 13).

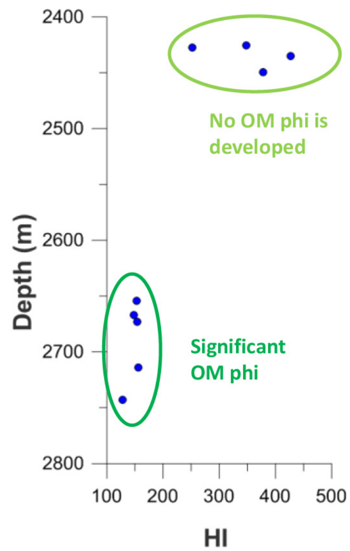
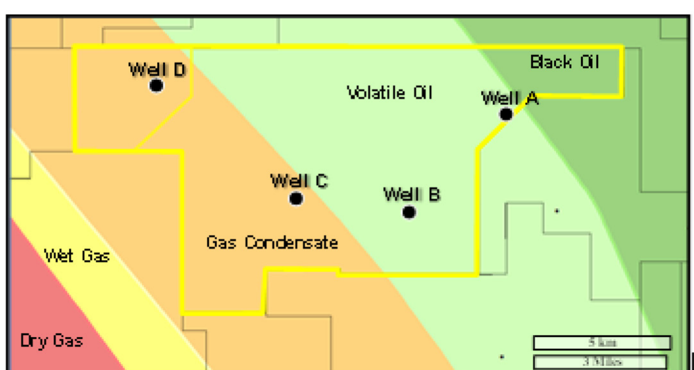


Figure 13—RockEval Hydrogen Index (HI) of the well "A" samples plotted as a function of current depth. In light green samples with no porosity reported in the organic matter. Deeper samples with lower HI (~150) present a significant OM phi.

Interpretation of visual kerogen analysis (vitrinite reflectance values) and produced fluid types (°API) in the wells are consistent and locate El Trapial area in the expected thermal maturity window from regional studies (Villar, 2014; Legarreta and Villar, 2011). Thermal maturity variation was defined not only laterally (along the area), but also vertically through Vaca Muerta in each well (Figure 14). Due to the extraordinary thickness of Vaca Muerta organic shale in this part of the basin (more than 350m) the estimated Ro value from top to base varies approximately 0.25% (Fantín and González, 2014).



Fluid Type / Criteria	Dry Gas	Wet Gas	Gas Condensate	Late Oil (volatile oil)	Peak Oil (black oil)	Early Oil (black oil)	Immature
Avg. Thermal Maturty (Ro%)		1,7	1,6	1,3	1,1	0,9	0,7
GOR (m3/m3)		17,000	3,500	530	260	90	
GOR (scf/STB)		100,000	20,000	3,000	1,500	500	
Oil Gravity (°API)		70°-56°	58°-48°	52°-45°	45°-35°	< 35°	

Figure 14—Map indicating El Trapial area in yellow. Different hydrocarbon windows and studied well locations are shown.

Well D is known to have gas-condensate at downhole conditions, while well B has oil at downhole conditions. There is no clear difference between the two T2 distributions. Although not having well-defined gas condensate diffusion coefficient and Hydrogen Index, the lack of difference between the two wells tends to show that those parameters may not be very different from light oil parameters.

As observed in Figure 15 it is not possible to identify a systematic effect of thermal maturity on the T2 distribution. There is no specific pattern associated with each maturity window.

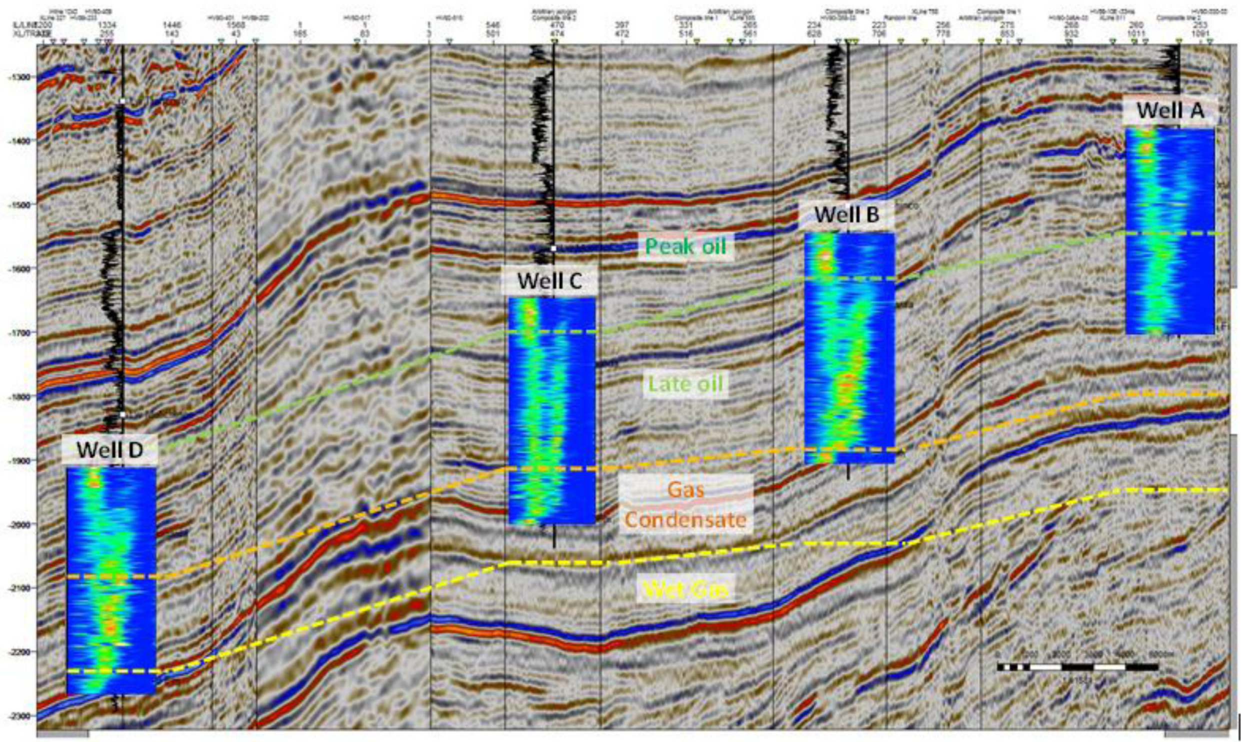


Figure 15—Vaca Muerta NMR distribution located into a seismic cross section with thermal maturity trends.

Facies Control

A detailed core description along more than 420 m of cores (Gonzalez Tomassini, et al 2014) and the integration with XRD, thin sections and TOC data, allowed the recognition of Vaca Muerta lithofacies and their vertical arrangement. Integrating those lithofacies with electrical logs allowed extending the interpretation to the non cored sections. The logs supporting the electrofacies are density, neutron porosity, compressional slowness, thorium, uranium and carbonate content, vertical resolution of these logs varies from 1 to 2 feet. The main electro facies are described in Figure 16.

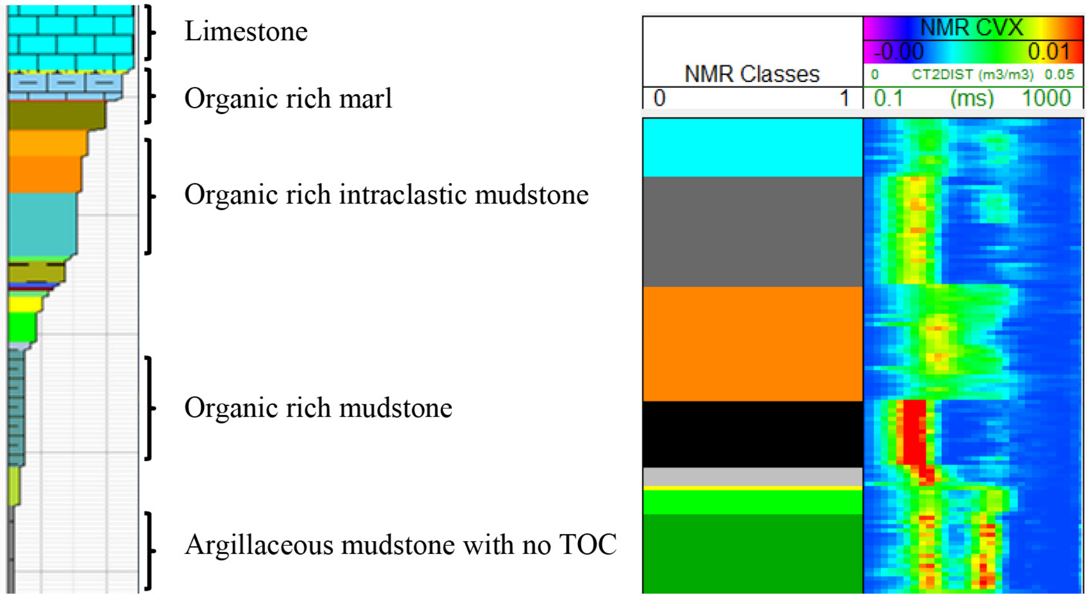


Figure 16—On the left main electrofacies description calibrated with stratigraphic core descriptions. On the right NMR Classes associated T2D on Well C

In parallel an automatic classification of NMR distribution patterns was done (Jain 2013). These patterns have a 1 foot resolution, using unfiltered NMR signal. Nine main patterns were identified and they are shown for Well C in Figure 16.

A good association is observed between electrofacies and NMR T2 distribution patterns (Figure 16). This association is better emphasized on figure 17B where the NMR D and other logs have been sorted by electrofacies. Limestones are generally associated with a weak bimodal distribution (cyan NMR class). Organic rich intraclastic mudstones are clearly defined by a bimodal distribution (green NMR class). Organic rich mudstone, mainly encountered at the bases shows a broad and blurry T2D (orange NMR class). Argillaceous mudstone shows clear low unimodal pattern with some sparse weak second mode, maybe due to more conventional pore system (black and grey NMR classes)

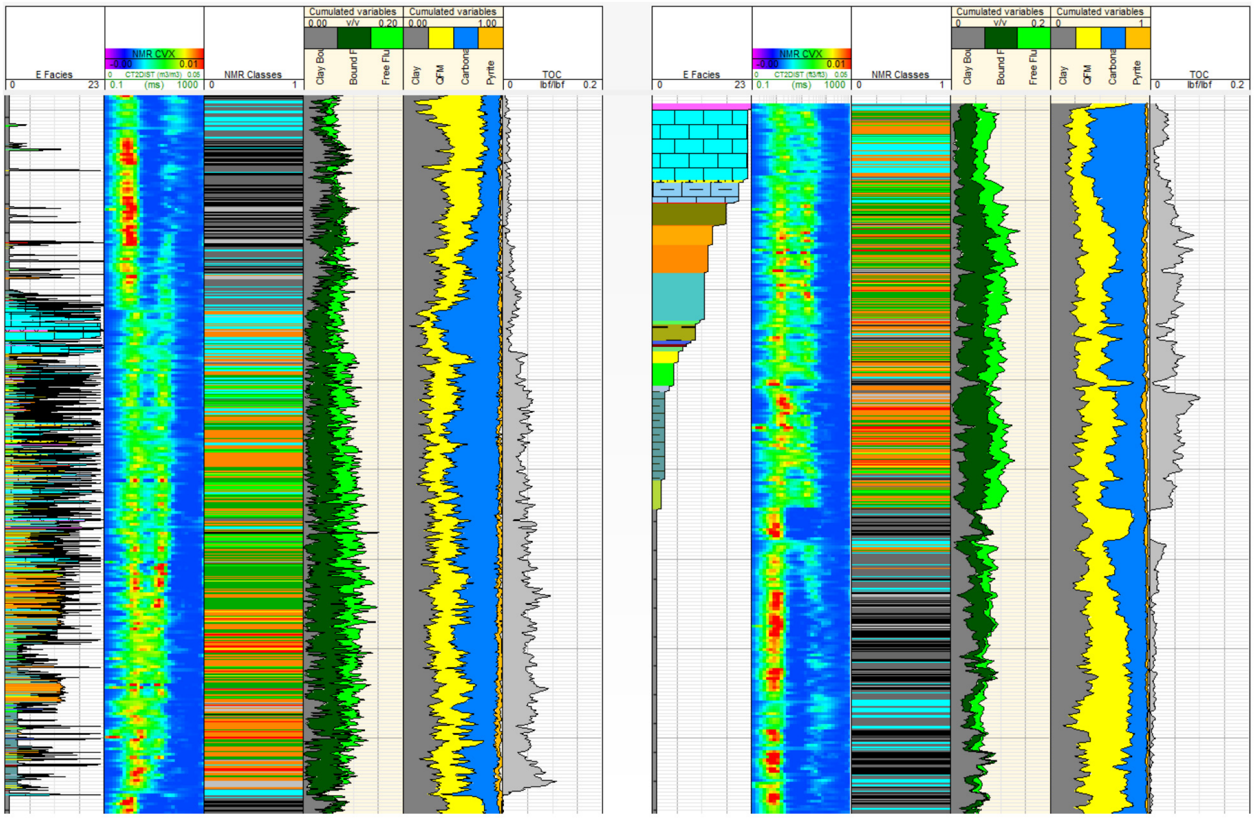


Figure 17—The left set of tracks shows depth logs of Well C. First track contains the electrofacies, second track the NMR T2D, third track the NMR classes, four track volumes of fluids associated with different pore systems, being grey the CBW, dark green the bound fluids and light green the free fluids. On the fifth track simple lithology model and on the last track TOC. On the right the tracks are the same but depths are sorted by electrofacies.

Integration of NMR T2 distribution pattern with laboratory studies

Subcritical Gas Absorption analysis was done in 40 samples distributed in wells A, B, and D, covering different maturity zones, organic richness and electro-facies. Figure 18 presents the SGA profiles from each well in the left sub-figures. A color coding represents the TOC, i.e. mainly the Kerogen content in each sample. A clear linear correlation exists between TOC and bin volume for the smallest pore diameter. The determination is generally the best for the smallest pores, as can be seen in the center subfigures of Figure 18. The correlation seems to decrease more rapidly for pore diameter larger than 10mn, and it is almost nil for pore diameters of the order of 20−40mn. Beyond this limit, a negative correlation arises. Many factors will affect the pore distribution, from the absolute porosity to kerogen maturity, but the above observations tend to demonstrate that the organic matter pores have the largest contribution for small pore diameters.

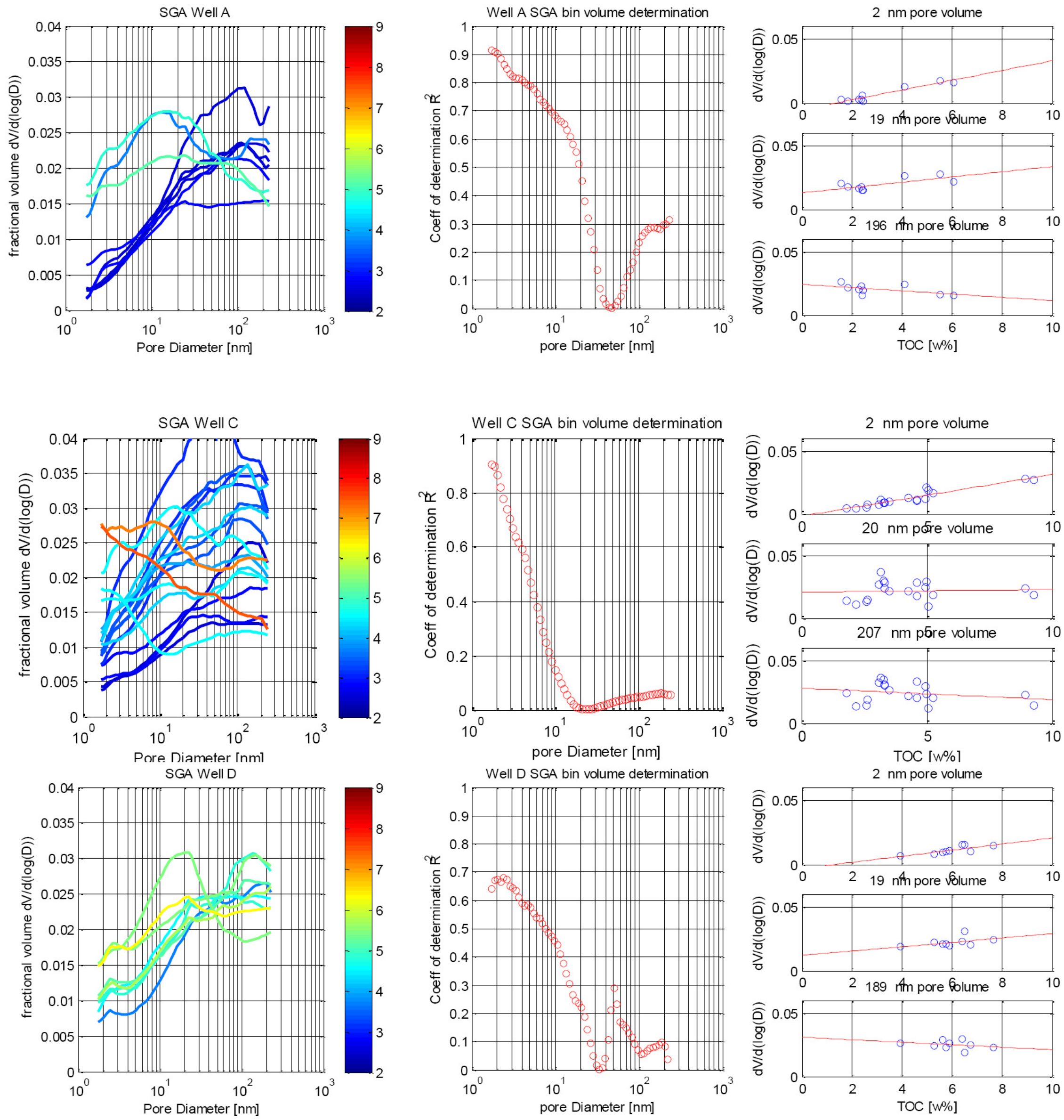


Figure 18—SGA for wells A.C and D. The subfigures on the left represent the bin volume versus pore diameter. The color coding represents the TOC (expressed in weight percent) measured on the sample. The sub-figures in the center represent the linear coefficient of determination from bin volume to TOC. The last sets of figures on the right illustrate the bin volume versus TOC correlation for 3 different pore diameters in each well.

Independently of pore size, there is also a correlation between the amount of organic matter and the organic matter associated pore volume Figure 19). The porosity in the organic matter is commonly expected to increase with increasing thermal maturity, nevertheless there is no such trend in Figure 19.

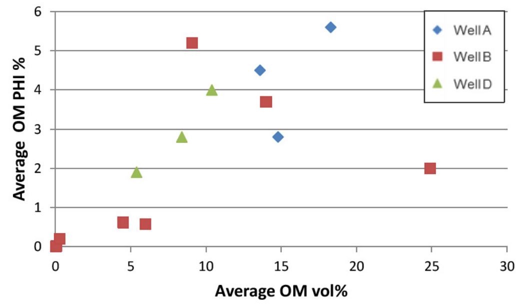


Figure 19—3D FIB-SEM data presents a good correlation between organic matter hosted pores and amount of OM.

In the deeper zone, thermally more mature, with higher TOC, pore sizes are dependent of the thermal maturity, being smaller in well A (less mature) and incrementing from well C to well D (Figure 20).

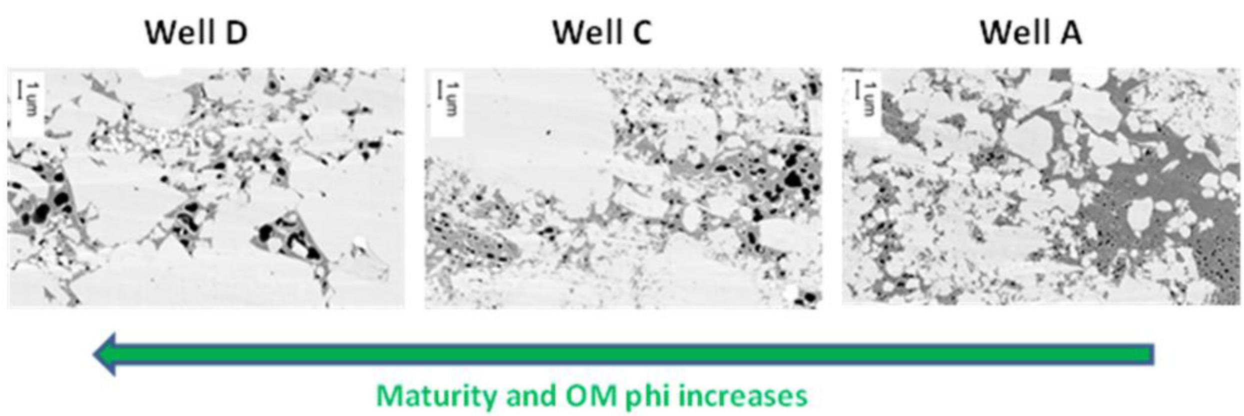


Figure 20—SEM images showing OM phi in wells A, C and D

In the SGA studies done after removing the organic matter from the samples, it can be observed that there was a significant amount of pores hosted in the organic matter.

Moving upwards in Vaca Muerta, there is an increment in the quantity of bigger pores. The shallower SGA bleached samples indicate that there is a low portion of organic matter pores, and that matrix pores (IM) are predominant.

The interpretation based on integrating SGA and NMR T2 distribution relates the T2 distribution single mode from the basal section with predominance of organic matter hosted porosity (OMphi) while the bimodal pattern is related with the increment of bigger and inorganic matrix pores (IMphi).

An additional piece of information to incorporate to the analysis derives from the proportion between IM and OM pores from 3D-FIB SEM. Although presenting a questionable representativeness, due to the scale of observation and the scarce amount of samples (13 samples from 3 wells), the results are consistent with the observation from SGA and NMR. The samples located in the Vaca Muerta lower section presents larger proportion of OM pores than IM pores, corresponding to pore structure group C of Kuila et al 2014, while in the upper section, the contribution of IM pores is more important, group B of Kuila (Figure 21).

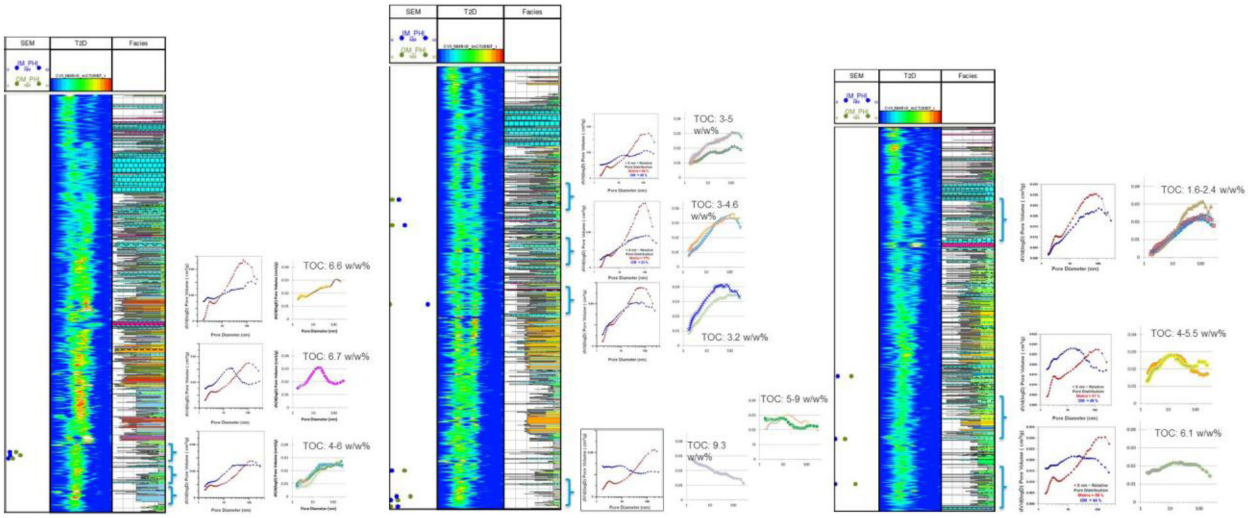


Figure 21—Integration between SGA, SEM and T2D from NMR in wells A, C and D. First track 3D FIB-SEM samples where blue dots indicate IM porosity and green dots OM porosity from 3D FIB-SEM calculation. NMR T2 distribution is on the 2nd track. On the 3rd track lithofacies. On the 4th and 5th track SGA and SGA with OM removal samples.

MICP study was done in more than 40 samples from three wells. The median pore throat diameter is estimated to range from 5 to 12 nm. In Figure 22 samples from well C show a pore size distribution from 4–30nm, where the median average is 8nm.

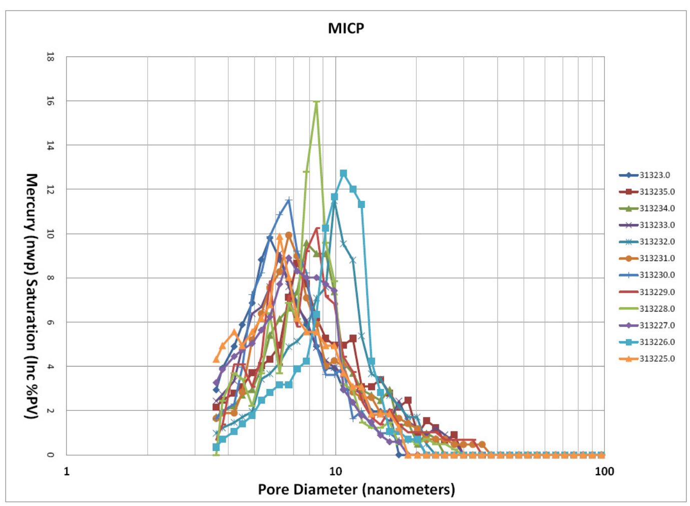


Figure 22—MICP of 12 samples from Vaca Muerta formation in well C.

Several publications indicate that combining MICP with SGA provides a comprehensive pore-size distribution analysis since each technique has a different measurement range (Saidian et al., 2014; Bustin et al., 2008). Results from Vaca Muerta in El Trapial area indicate that pore throats from MICP are not bigger than 30nm and pore diameters from SGA range between 2and 200nm. Note in Figure 23 that for different pore size distribution in SGA (blue curve), the MICP (orange curve) is very similar, suggesting that there is no significant change of pore throat size through Vaca Muerta.

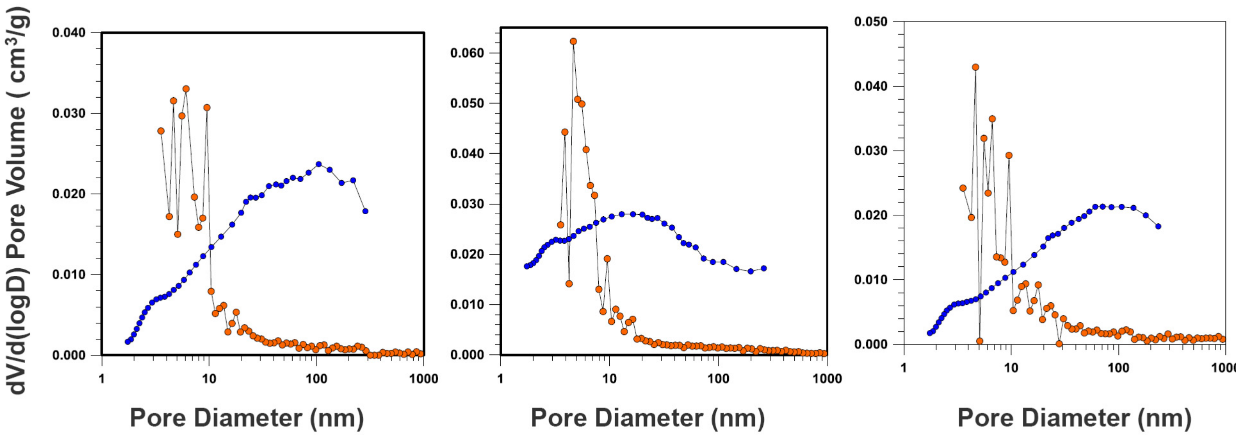


Figure 23—Comparisson between MICP (orange dots) and SGA (blue dots) on the same sample

Conclusions

- There is a vertical variation in pore (size, amount and type) distribution through Vaca Muerta. These variations are controlled by many factors.
- There is a relation among the NMR T2 distribution and thermal maturity, organic matter content, compaction and facies. Based on the analysis and understanding of their contribution, four main patterns were identified and supported by laboratory data:

1. Unimodal T2 Distribution at the base of Vaca Muerta where organic rich mudstones are present. OM phi is predominant and increases its size with increasing thermal maturity while IM phi decreases.
2. Bimodal T2 Distribution in the middle section where TOC content is higher than 2%. Facies includes intra-clastic mudstones, marls and limestones. The first mode contains CBW, a fraction of bitumen and OM phi. The second mode represents the contribution of a larger pore system probably associated with inorganic porosity.
3. Broad and blurry T2 Distribution observed also in the middle section mainly associate with organic rich mudstones. In this section both types of pores are present and it is suspected that a complex fluid system generates this T2 pattern.
4. Unimodal T2 Distribution in the Upper section of Vaca Muerta associated with the non-organic mudstones with high clay content. Porosity is mainly due to clay bound water.

- This integrated analysis demonstrates that Vaca Muerta in El Trapial area pores and pore throats sizes should allow mobility of oil molecules. This indicates that production should have a contribution from matrix.
- The presence of inorganic pores (IP phi) linked to the bimodal distribution may be associated with the higher productivity oil zones.
- In the basal zones the OM phi is predominant. In zones with high-enough thermal maturity, bigger OM phi can be developed enabling the production from this zone. The different nature of pore may require a stimulation strategy different than the upper zones.
- Nuclear magnetic Resonance demonstrated to be a powerful source of information for characterizing and understanding pore system in shale rocks. NMR is a strategic tool to be included in exploration/pilot wells log suite to help define target intervals in vertical wells and landing zones for horizontal wells.
- A dedicated acquisition and T2 inversion is key to optimize NMR information.

- An important factor that was not investigated in this contribution is the effect of fluid type (water, oil, bitumen) and properties (Hydrogen Index, Diffusion effect) in the NMR T2D NMR lab measurements on cores including re-saturation, T1-T2 measurements are a necessary input for this future work.

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References

Alcantar-Lopez L. and Chipera S. J, 2013, Improving Our Understanding of Porosity in Source Rock Reservoirs through Advanced Imaging Techniques, Unconventional Resources Technology Conference, August 12–14, Denver, United States, SPE 168916/URTeC 1619700.

Bohacs K. M., Passey Q. R., Rudnicki M., Esch W. L., and Lazar O. R., 2013, International Petroleum Technology Conference, March 26–28, Beijing, China, IPTC 16676.

Bustin R. M., A. M. M. Bustin, X. Cui, D. J. K. Ross and V. S. Murthy Pathi, 2008. Impact of Shale Properties on Pore Structure and Storage Characteristics. SPE119892.

Clerke, E. A., Allen, D. F., Crary, S. C., Srivastava, A., Ramamoorthy, R., Saldungaray, P.,Savundararaj, P., Heliot, D., Goswami, J., Bordakov, G., Wireline Spectral Porosity Analysis of the Arab Limestone-From Rosetta Stone to Cipher, paper D, SPWLA, 2014.

Fantín, M. and González R., 2014, Primeros Pasos en la Evaluación de Vaca Muerta como Reservorio No-Convencional en el Bloque El Trapial, *IX Congreso de Exploración y Desarrollo de Hidrocarburos, IAPG,* Mendoza, Argentina.

Gonzalez Tomassini, F., Kietzmann D., Fantín M., Crousse L. and Reijenstein H., 2014, Estratigrafía y análisis de facies de la Formatión Vaca Muerta en el área de El Trapial, Cuenca Neuquina, Argentina, *IX Congreso de Exploration y Desarrollo de Hidrocarburos, IAPG,* Mendoza, Argentina.

Hook, P, Fairhurst, D., Rylander, E., Badry, R., Bachman, N., Crary, S., Chatawanich, K., Talyor, T., Improved Precision Magnetic Resonance Acquisition: Application to Shale Evaluation, SPE 146883, 2011.

Jain, V., Minh, C. C., Heaton, N., Ferraris, P., Ortenzi, L., Ribeiro, M. T., Characterization of Underlying Pore and Fluid Structure Using Factor Analysis on NMR Data, Paper TT, SPWLA, 2013.

Jian T., Rylander E., Singer P. M., Lewis R. and Sinclair S. M., 2013, Integrated Petrophysical Interpretation of Eagle Ford Shale with 1-D and 2-D Nuclear Magnetic Resonance (NMR), SPWLA 54th Annual Logging Symposium, June 22–26.

Kausik, R., Fellah, K., Rylander E., Singer P. M., Lewis R. E., Sinclair., “NMR Petrophysics for Tight-Oil Shale Enabled by Core Re-Saturation”, *Society of Core Analysts,* SCA 2014–28, 2014.

Kuila U., McCarty D., Arkadiusz Derkowski, Fischer T. B., Topoór T., Prasad M., Nano-scale texture and porosity of organic matter and clay minerals in organic-rich mudrocks, *Fuel* **135** (2014) 359–373. 2014.

Kuila U., Prasad M., Derkowski A., McCarty D., Compositional controls on mudrock pore-size distribution: an example from niobrara formation, SPE Annual Tech. Conference Exhib., San Antonio, Texas, USA: Society of Petroleum Engineers, SPE 160141; 2012.

Legarreta L. and Villar H., 2011, Geological and Geochemical Keys of the Potential Shale Resources, Argentina Basins. AAPG Geoscience Technology Workshop, "*Unconventional Resources: Basics, Challenges, and Opportunities for New Frontier Plays,*" Buenos Aires, Argentina, June 26–28, 2011.

McKeon, D., Cao Minh, C., Freedman, R., Harris, R., Willis, D., Davies, D., Gubelin, G., Oldigs, R., and Hurlimann, M., An Improved NMR Tool Design for Faster Logging, paper CC, SPWLA, 1999.

Nelson P. H., January 2010, It's A Small World After All – The Pore Throat Size Spectrum, *Search and Discovery Article #50218*.

Nelson, Philip H., 2009, Pore-throat sizes in sandstones, tight sandstones, and shales. *AAPG Bulletin,* v.**93,** No. 3 March, PP.329–340.

Rylander E., Singer P., Jiang T., Lewis R., McLin R., Schlumberger and Steve Sinclair, 2013, NMR T2 Distributions in the Eagle Ford Shale: Reflections on Pore Size, SPE164554.

Saidian M., Kuila U., Rivera S., Godinez L., Prasad M., 2014, Porosity and Pore Size Distribution in Mudrocks: *A Comparative Study for Haynesville, Niobrara, Monterey and Eastern European Silurian Formations,* URTeC 1922745.

Villar, H., 2014, Informe geoquímico- Evaluatión de los pozos en El Trapial, Cuenca Neuquina, Informe inédito, GeoLab Sur S. A.