# 3D PORE PRESSURE PREDICTION CASE IN A TIGHT GAS RESERVOIR, RÍO NEUQUÉN, ARGENTINA

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## RESUMEN

Este caso de campo busca cuantificar la magnitud de las anomalías de presión y entender el mecanismo de sobrepresión dominante en el reservorio de gas apretado de Rio Neuquén. Para alcanzar este objetivo se construyó un modelo de presión de poral basado en atributos sísmicos y análisis de datos multi-pozo. El modelo permitió establecer también posibles dependencias entre el desempeño del reservorio y dichas anomalías de presión.

El modelo matemático emplea como input tanto las velocidades sísmicas de la migración pre-apilado en profundidad (PSDM) como las velocidades resultantes de la inversión simultánea, estableciendo relaciones entre la respuesta elástica de la roca y la presión poral a través de una serie de transformadas esfuerzo efectivo-velocidad. El modelo también considera el análisis multi-variable de otros parámetros que afectan la respuesta sísmica, incluyendo la porosidad, contenido de arcillas y el esfuerzo efectivo, empleando una metodología similar a la presentada por Sayers (2003). Los datos de campo y ensayos de laboratorio soportan los resultados obtenidos.

Como conclusión del análisis se evidenció que las regresiones de velocidad tienen una fuerte influencia de los esfuerzos efectivos. El comportamiento sensible a los esfuerzos de la roca reservorio fue confirmado mediante los ensayos de laboratorio de velocidades ultrasónicas y los esfuerzos efectivos derivados de las pruebas de presión. A nivel de pozo también se observaron efectos litológicos y de la porosidad en la respuesta sísmica, no obstante, ellos no fueron considerados en el modelo 3D debido a limitaciones en los datos de entrada.Las Velocidades de la inversiónsísmica condujeron a un modelo de presión poral más representativo que el obtenido a partir de las velocidades de laúltima iteración tomográfica de la PSDM.

El estudio sugiere que múltiples mecanismos de sobrepresión tipo-II están presentes en el área de Rio Neuquén, incluyendo transferencia lateral, generación de hidrocarburos, expansión de fluidos y carga tectónica. De ellos, se cree que la principal causa de la anomalía de presión está asociada a la presencia de la roca madre sobrepresionada (formación Los Molles) en la zona basal de la cuenca, la cual aporto sobrepresióna los reservorios (formaciones Lajas y Punta Rosada) a través de los sistemas de falla principales; esta sobrepresión fue preservada gracias a la presencia de un control estratigráfico, caracterizado por la presencia de varias discordancias y superficies de inundación a lo largo del reservorio.

Este caso de estudio muestra cómo se puede modelar la presión poral en ciertos reservorios de arenas apretadas que exhiben un comportamiento sensible a los esfuerzos. Un pozo perforado recientemente fue usado como pozo de observación, mostrando la precisión y solidez del modelo de presión poral construido.El modelo de presión de poro permite además la cuantificación de las reservas de gas y la determinación de sweet spots para la perforación de nuevos pozos, haciendo del modelo predictivo 3D de presiones una poderosa herramienta para la explotación y plan de desarrollo de campos de gas apretado y posiblemente de otros no convencionales.

## INTRODUCTION

Rio Neuquen is a gas field located 30 km NNO of the Neuquen city, covering part of the provinces of Neuquen and Rio Negro in Argentina (Figure 1).Historically, the field has produced from the conventional reservoirs of Mulichinco, Quintuco, Tordillo and Lotena formations, nowadays in the declination stage. Below these formations appear the unconventional reservoirs of Punta Rosada (Digregorio 1972) and Lajas (Weaver 1931).

These formations are part of a "Basin Center Gas System (BCGS)", asystem fully developed in the Cuyo Group (Dellape 1978), composed by Los Molles (Weaver 1931) (source rock), Lajas and Punta Rosada formations (main reservoirs); these reservoirs are "Tight Sand" type. The BCGS are characterized by covering large areas, having great vertical continuity and abnormally pressurized. The reservoir quality is typically poor, with a generalized very low permeability and a water contact not clearly defined; furthermore, the reservoir zone is in direct contact or very close to the source rock. In Rio Neuquen all these characteristics are present; Lajas and Punta Rosada formations are "Tight" reservoirs, with an average permeability below 0.1md, averaging 0.03md. The reservoir zone is a 900-meterthickness overpressurized gas-saturated sand interval in direct contact with the source rock, Los Molles formation. There is no evidence of water contact.

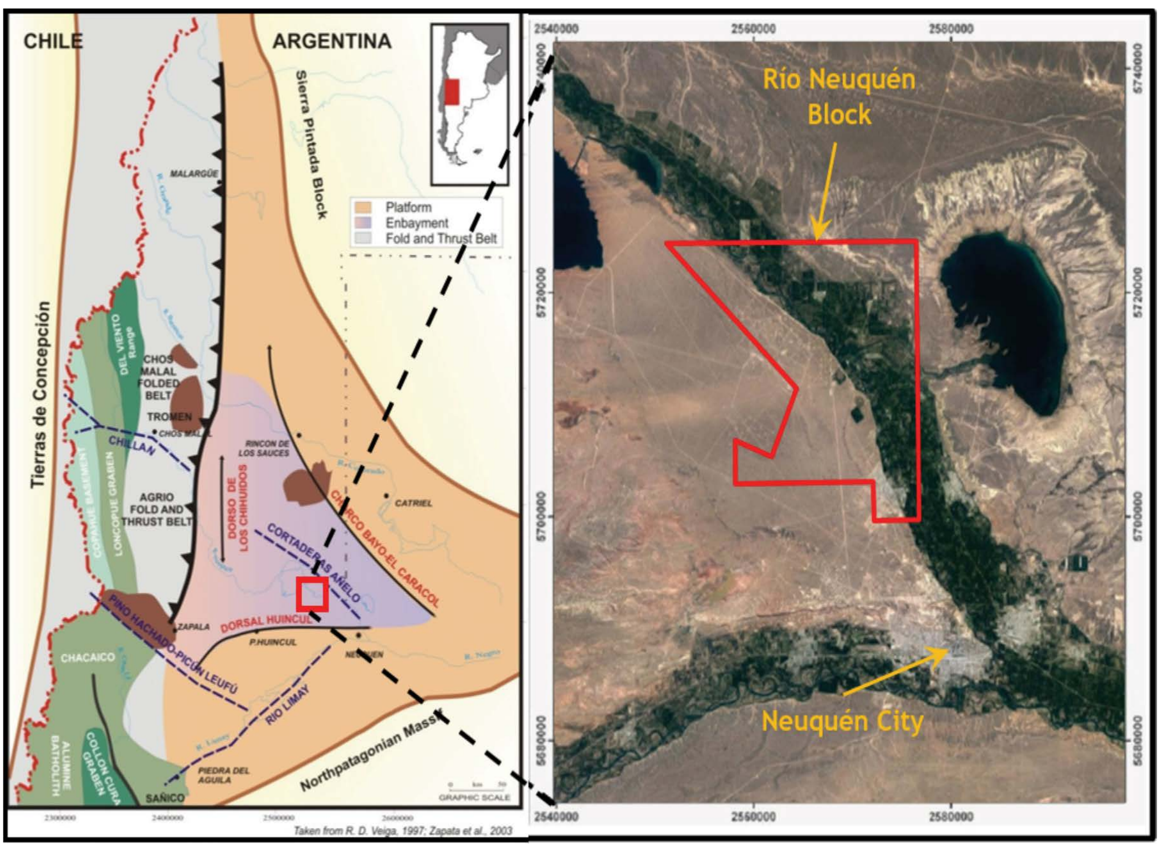


Figure 1. Location Map

Multi-stage hydraulic fracturing is required to commercially produce the gas reserves along the reservoir zone; however, wells productivity has been strongly affected by net thickness and pore pressure, the higher the pore pressure the higher the productivity (gas movement is easily achieved when overpressures exist), same reasoning applies for net thickness. Storage capacity is also affected by overpressure level, the higher the overpressure the higher the gas reserves. For all these reasons, knowing the spatial distribution of the overpressure anomaly has been a key factor for both well planning and field development strategy.

A predictive pore pressure model was built using available well data and seismic. Initial pore pressures were estimated from mini-falloff and DFIT test interpretation, previous to the fracturing stage. The tests were not performed in all the wells so pore pressures are not available for all the wells or intervals. This predictive model helped to understand the petroleum system and identifying the location of pressure anomalies for sweet spots detection, well location, fracture staging and reserves estimation.

The pore pressure cube was built from a high-resolution velocity field extracted from PSDM processing and AVO Simultaneous Seismic Inversion along the 240 km2 of seismic volume. The PSDM also helped to optimize the seismic image and reach a better definition of the structural framework required to build the pore pressure model. Sixteen wells were used as offset wells for seismic processing while twenty-one wells were used for pore pressure modeling, providing the control points required for calibration.

## GEOLOGICAL FRAMEWORK AND PETROLEUM SYSTEM

The structure of the Rio Neuquen field can be described as a broad anticline, elongated in the SW-NE direction, limited to the north by a series of NW-SE faults. These faults are interpreted as normal basement faults, which were inverted (Figure 2). The anticlinal structure is crossed by a series of normal faults, with a NNE-SSO azimuth, conforming a small collapse graben at the crest of the anticline.

The complete stratigraphic column for the field is presented inFigure 2. The tight gas reservoir zone is located inside the Cuyo Group (Dellape *et al.*, 1978). This interval begins with black shales deposits of a deep marine environment, assigned to Los Molles Formation (Weaver 1931), which is the source rock of the system and has two sections with distinctive characteristics. Over these deposits begins the progradation of a series of deltaic and fluvial facies corresponding to the Lajas and Punta Rosada formations,consisting of more than 1000metersof sandstones, conglomerates and interbedded shales, these deposits constitute the gas reservoirs of the Cuyo Group. They are characterized by having porosities less than 10%; very low permeabilities, between 0.0001 to 0.1 mD and sub-irreducible water saturation ranging from 10% to 60%. All these characteristics correspond to a “Tight”reservoir.

During the Cuyo Group deposition period occurred a series of tectonic pulses that were recorded as unconformities (Berdini *et al.*, 2002). These have been identified in the seismic sections, playinga significant role in the overpressure distribution and trapping.

## GENERATION, MIGRATION AND ENTRAPMENT

### Hydrocarbon Generation

Los Molles formation has been identified as the primary source of Lajas and Punta Rosada gas. It was deposited during the first marine ingression of the basin, filling the hemigrabens formed during the “Rift” stage (Gulisano *et al.*, 1984) (Figure 3).

In the Rio Neuquen block it is possible to recognize two different sections within Los Molles formation; a lower one with type II / III kerogen and an upper section with type III kerogen (Figure 4).

The maturity reached by the Lower Section is 1.6% Ro and according to the performed 2D modeling, the hydrocarbon expulsion would have begun between 140 and 150 Ma (early Cretaceous). This first expulsion period produced mainly oil. By this time, the main structure of the field was already configured as an anticline and part of the hydrocarbons generated were trapped in Lajas and PuntaRosada reservoirs.

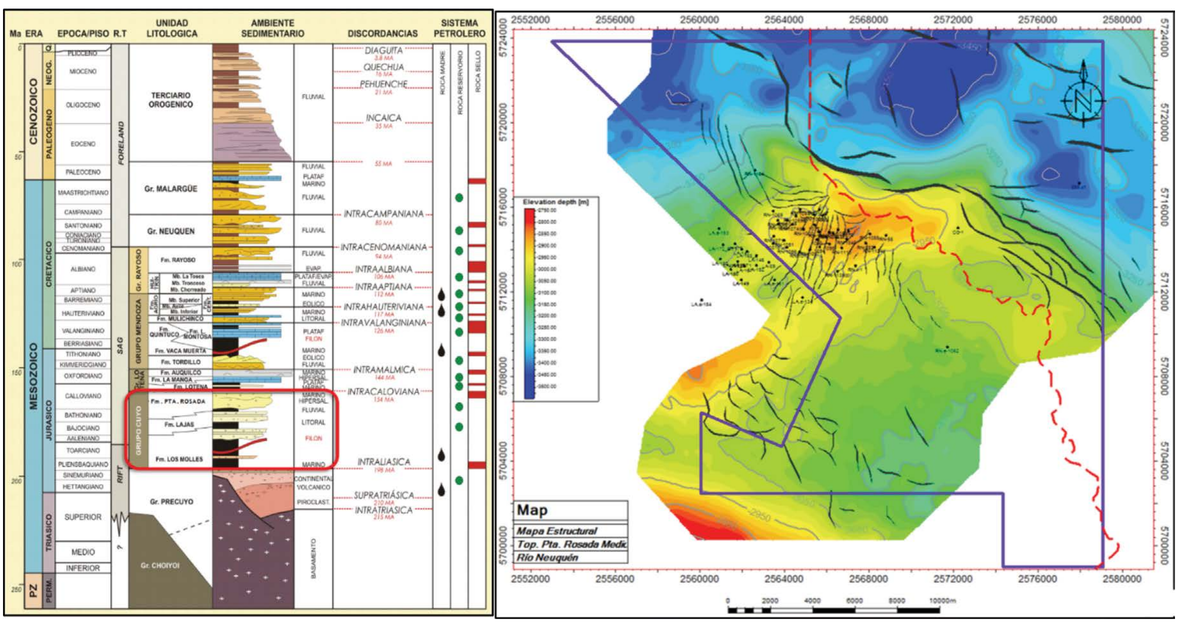


Figure 2. Stratigraphic Column (left) and Top Punta Rosada Structural Map (right)

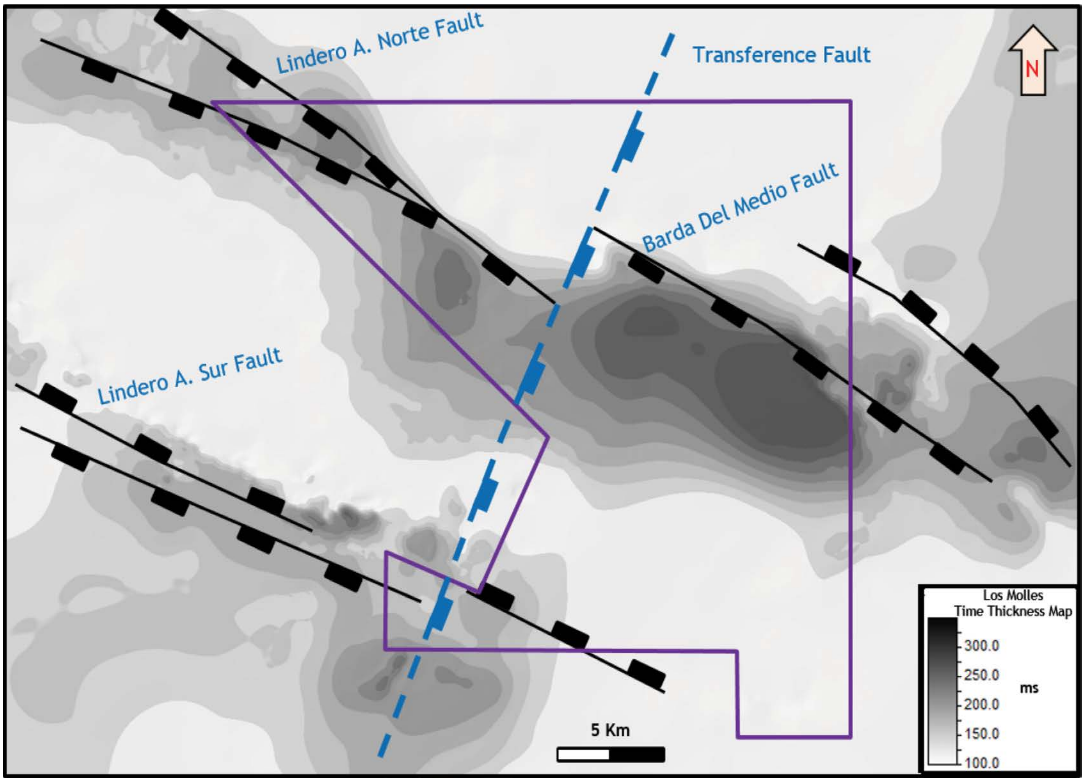


Figure 3. Los Molles Formation Isopach map

The Upper Section reached a maturity of 1.2% Ro, initiating a second expulsion period between 115 and 120 Ma (Early High Cretaceous), when most of the reservoirs already had tight properties (Figure 5).The thermal state reached at that time allowed the "in situ" cracking of

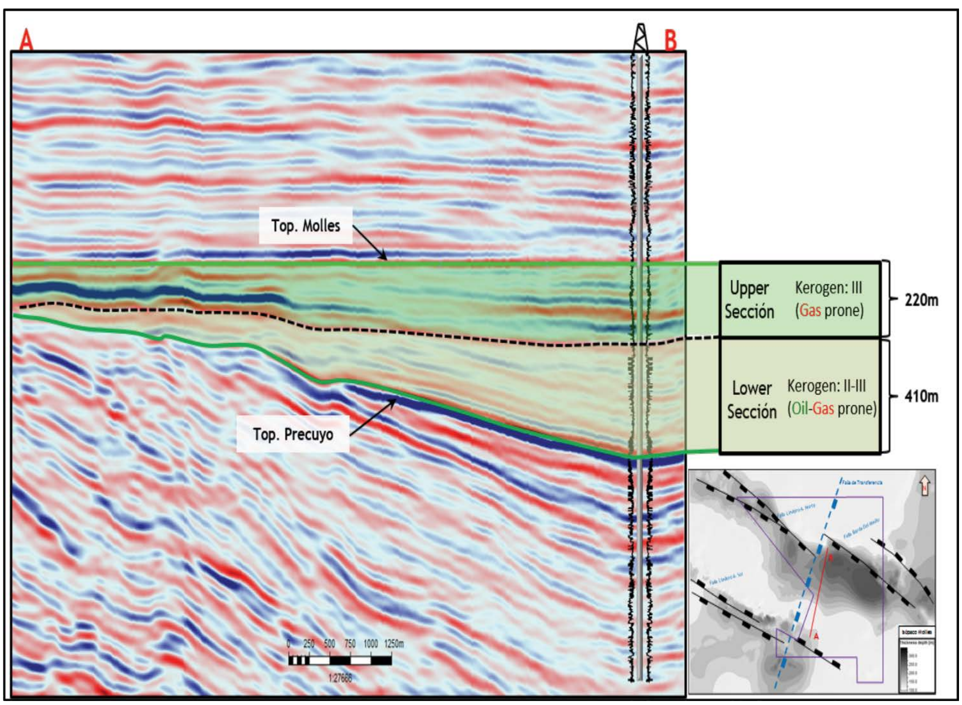


Figure 4. Seismic section, showing the Upper and Lower Los Molles Formation

the hydrocarbons, coming from the lower section of Los Molles and trapped in Lajas and Pta. Rosada formations. This phenomenon, together with the gas migration of both sections, would be responsible for the elevated levels of overpressure in the tight reservoirs (Berdini *et al.* 2011).

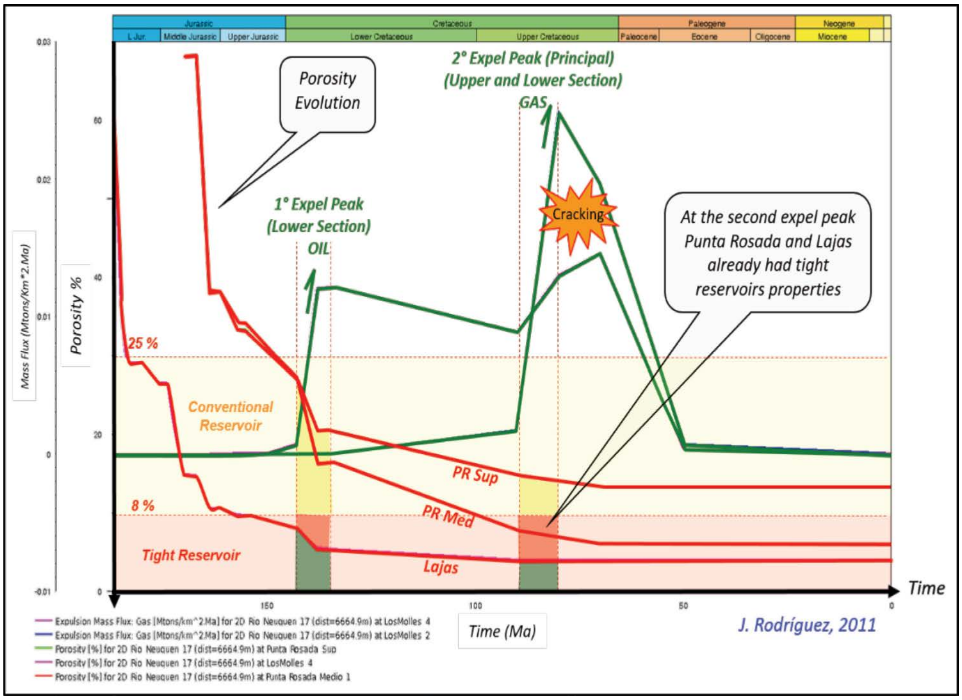


Figure 5. Porosity and maturity evolution with time

## Hydrocarbon Migration

The migration process would have occurred vertically from Los Molles, through faults, mainly and to a lesser extent, through penetrating fissures (Sibson; 2001), thesesub vertical fissures would allow the migration of hydrocarbons from Los Molles to Lajas formation. Even more, in those field sectors near to the fault systems the overpressurized hydrocarbon column will rise higher, thus reaching the top of Punta Rosada formation. Conversely, those field sectors far apart from the fault system showed a lesser overpressure, mainly restricted to the basal reservoirs of Lajas Formation, and consequence only of the action of penetrating fractures only (Figure 17).

## Hydrocarbon Trapping

The trapping mechanism in this type of systems occurs because the gas generation speed exceeds the gas dispersion capacity at the top of the low permeability zone, generating a “pressure trap”. As the generation and migration of HC continues an increase in pore pressure occurs, which greatly exceeds the normal pressure gradient. As shown in Figure 5, at the time of the second hydrocarbons expulsion peak, the Punta Rosada and Lajas reservoirs already had "Tight" properties (very low porosity and permeability).

## PORE PRESSURE PREDICTION METHODOLOGY

Most of the pore pressure modeling techniques are based in the vertical effective stress concept proposed by Terzaghi (1968, 1923). If overburden and effective stress are known then pore pressure can be estimated using such approach. From these variables, overburden can be calculated from a density cube, obtained mainly from seismic inversion or log data (used in this case). Effective stress, on the other hand is a more complex variable. Typically, it can be obtained from empirical correlations and models based on effective stress-velocity transforms, from seismic velocities and acoustic log data (Noeth 2006). These relationships must be known in advance, they should honor real data (pressure measurements and indicators) and consider also other variables that could affect the velocity response, masking the real effective stress state. Some of these variables include lithology, porosity and interstitial fluids, all of them affecting the elastic response in tight formations, especially due to the presence of low porosities, lithological variations and gas.

The effective stress-velocity transforms can be obtained from back-analysis and must account for the overpressure mechanism. Different transforms represent the loading and unloading paths during overpressure generation. Each zonein the reservoir could behave differently, probably having different loading and unloading curves. Considering all these effectsadd more complexity to the pore pressure prediction modeling.

The effective stress velocity-transforms can be written in the form of Equation 1,representing the loading path (also referred as the virgin curve) and Equation 2 is used for modeling the unloading path. Both equations are described in the Bowers approach (1995).

$$\boldsymbol{v = v_0 + A * \sigma_{eff}^{B}} \qquad \text{Equation 1}$$

$$\boldsymbol{v = v_0 + A \left[\sigma_{max} \left(\frac{\sigma_{eff}}{\sigma_{max}}\right)^{\frac{1}{U}}\right]^{B}} \qquad \text{Equation 2}$$

Where:v is actual Velocity (ft/s), $v_0$ is the Velocity when effective stress is cero (ft/s), $\sigma_{eff}$ is the actual Effective stress, $\sigma_{max}$ is the maximum effective stress, A is the Bowers coefficient, while B and U are the loading and unloading Bowers exponents respectively.

Figure 6 represents a typical workflow for 3D pore pressure modeling. The workflow can be divided in the following steps: obtaining a high-resolution velocity field, 1D pore pressure modeling (1DPP) and calibration to well data and 3D pore pressure modeling (3DPP) using seismic attributes. The 1DPP modeling is the phase where the effective stress-velocity transforms are built and the overpressure mechanisms are determined.

Inputs for pore pressure modeling include the geological model, lab tests, well logs, petrophysical analysis and the seismic velocities.Velocity and density from well log data is critical for building the low frequency model required for seismic inversion and 1D pore pressure modeling. Petrophysics is required whenever multi-variable analysis is performed to account for lithology, porosity and fluid effects in the elastic response of Punta Rosada and Lajas reservoirs. Nonetheless, expanding this analysis to the 3D space requires a lithocube and a 3D petrophysical modeling.

There is information of 21 wells in the Rio Neuquen area containing this information, besides the structural model and the high resolution seismic velocity cube from both PSDM and simultaneous AVO inversion.

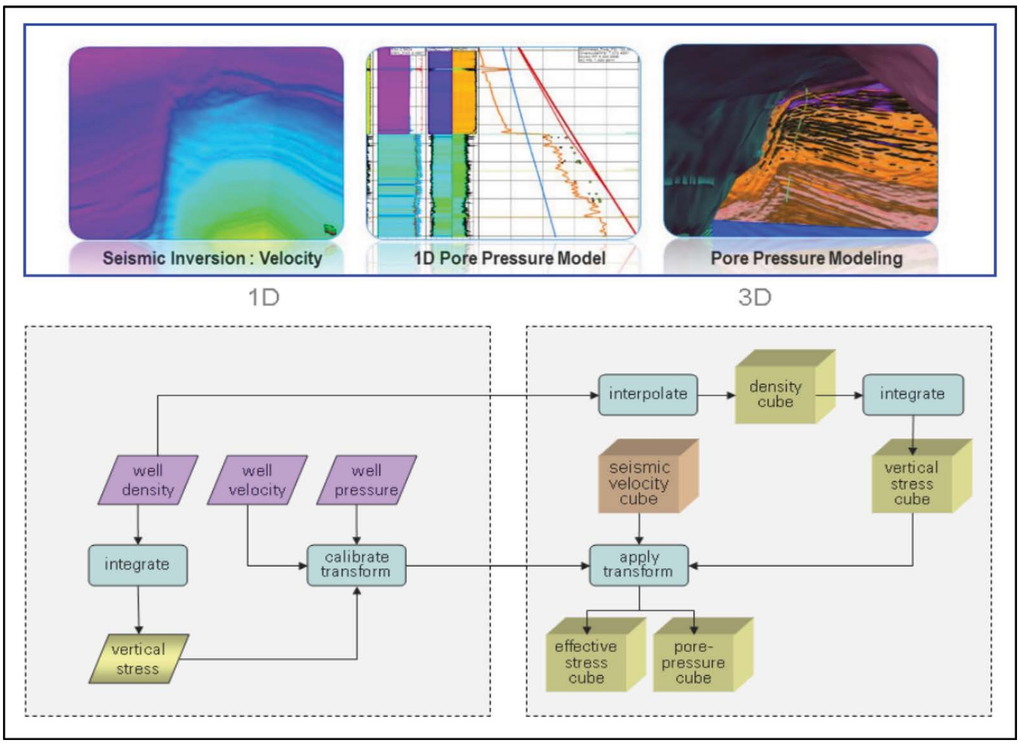


Figure 6. Pore pressure cube modeling workflow using seismic inversion

## Velocities from Seismic Processing

High resolution velocities were obtained from two complementary processing: PSDM and simultaneous inversion. PSDM processing helped to obtain not only a better structural framework but also a first interval velocity field for pore pressure estimation (De Coevering *et al.*, 2007). The simultaneous inversion produced a more consistent and representative velocity model for

1D and 3D pore pressure calculation; it also provided the density cube required for overburden calculation and the VPVS for lithology and other quantitative seismic interpretation routines. Bachrach *et al.* (2007) presents a similar workflow for pore pressure modeling using high resolution seismic velocities.

The first attempt to construct the pore pressure model was made with the seismic velocities coming from the last iteration of the pre-stack depth migration (PSDM). These process velocities, although they had been picked every 500 m and have enough detail for an adequate correction of the NMO in successive stages of the process, they were insufficient (due to their low frequency content) to resolve the pressure differences expected between the levels of Punta Rosada formation and Lajas formation.

The first result of the pore pressure volume using those velocities showed significant differences in absolute values between the predictive cube and the PLT results.

Because of these differences, it was decided to make a simultaneous seismic inversion to improve the vertical resolution of the velocity volume and, at the same time, to obtain a density volume that could be used to estimate the normal compaction tendency and a lithocube.

Next is the workflow that was used to conduit this inversion:

The angle gathers from the PSDM migration were conditioned applying a mute and dividing the set of gathers into a lower section comprising from 3 seconds to the top of the Lotena Fm and an upper section comprising from Lotena Fm to 0 seconds. In the lower section, multiple reflections were removed using Radon filter.

From these two set of gathers, two simultaneous inversions were made. The reason for the division is that both the amplitudes and the frequency spectrum are different in both times and consequently the wavelet (Figure 7).

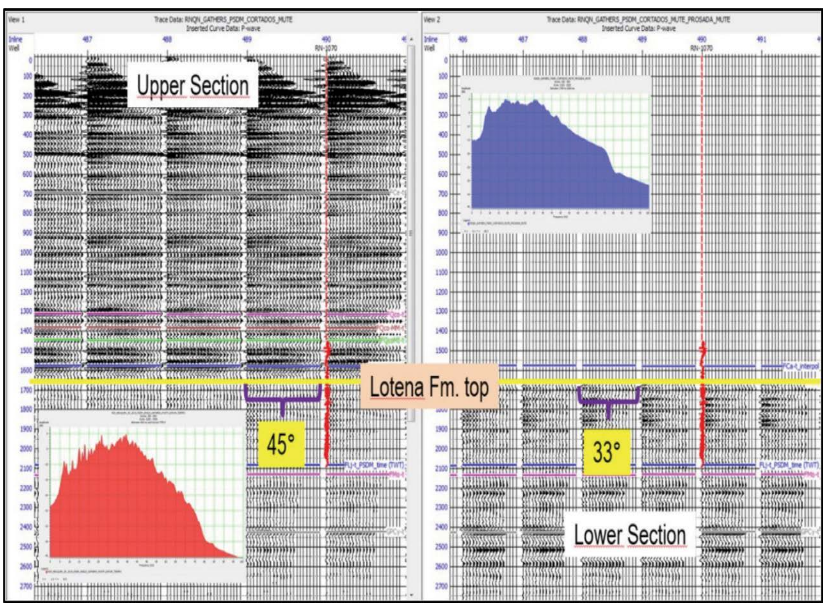


Figure 7. Conditioned gathers and frequency spectrums (upper and lower section)

A unique low frequency model was built using 3D modeling software, based on the PSDM migration velocities and using the P wave, S wave and density log profiles of a group of 16 wells, as well as 8 seismic horizons interpreted in double travel time corresponding to the following formation tops: Los Molles, Lajas, Lotena, Catriel, Middle Quintuco, Upper Quintuco and Centenario. The methodology consisted of generating a 3D grid with 100m x 100m x 8ms cells where the Vp log, Vs log and density log filtered at 30 Hz were populated using PSDM migration velocities as a secondary variable. As products, three volumes were obtained: P wave, S wave and density, which were then filtered in the frequency domain, according to the analysis conducted prior to inversion (12-18 hz).

Three ranges of angles were selected from the angle gathers for the upper section: near (1-16 °), middle (16-30 °) and far (30-45 °) and three ranges of angles from the angle gathers for the lower section: near (1-12 °), middle (12-22 °) and far (22-33 °). An average wavelet was extracted for each set of gathers, obtaining 6 wavelets, three corresponding to the upper section and three corresponding to the lower section.

The two inversions were made and the results were concatenated, that is, a unique P impedance volume, a unique S impedance volume and a unique density volume were obtained (Figure 8). The QC analysis concluded that the P impedance volume and S impedance volume have a very good correlation with the blind wells but the density volume did not have the sufficient quality, neither for the calculation of the overburden nor for the estimation of the lithocube.

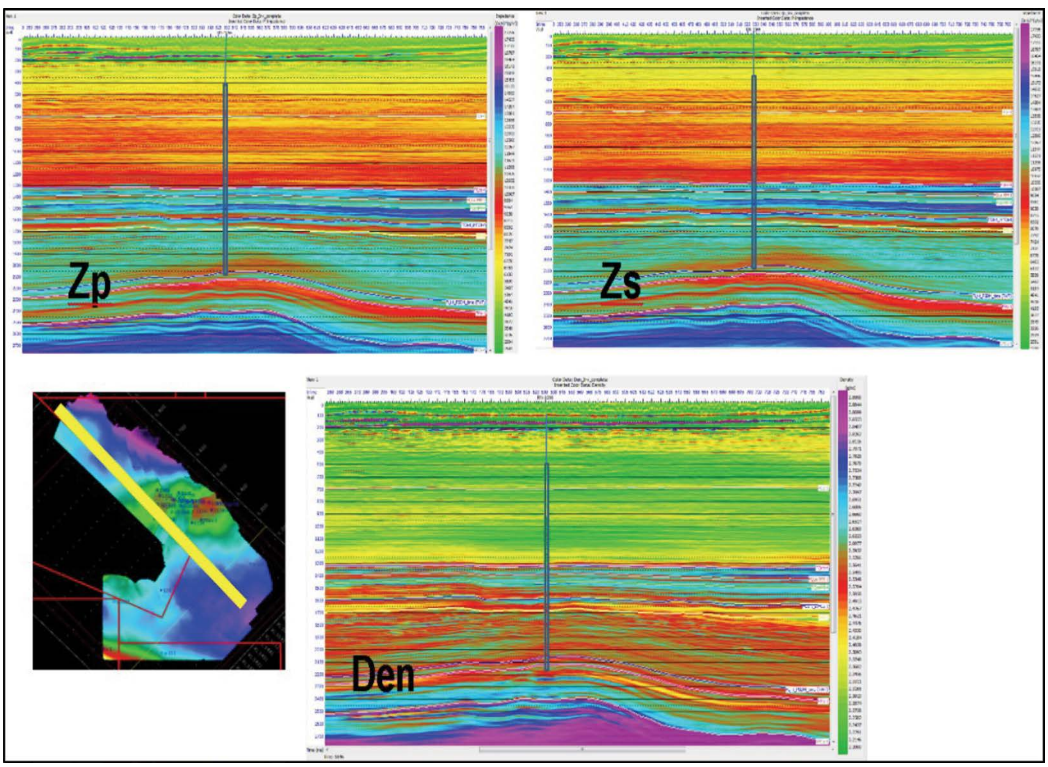


Figure 8. Products obtained from simultaneous seismic inversion

## Offset well Pressure data

The development wells are concentrated in the central part of the block as presented in Figure 2, with only one well located in the south-east region. There are no wells in the northern nor southern areas of the block. This inhomogeneous well distribution will impact the model uncertainty in those specific areas due to a poor lateral control in the seismic processing and inversion. Hence, azimuthal variation is not well constrained.

The pore pressure model was calibrated against Mini Falloff and DFIT data from 21 wells, used as control points. The pressure readings cover a long overpressurized interval of 1000 meters, from Punta Rosada to Lajas formation. There are also some pressure tests in the almost normally pressurized Lotena formation located just above the overpressurized interval. This zone serves as calibration point for the loading curve.

Figure 9 shows the equivalent pressures for each control point. The maximum overpressure is in the lower part of the reservoir zone, just bigger than the pressure anomalies at the reservoir top. In general, the Punta Rosada-Lajas zone has pressure gradient ranging from 0.58-0.70 psi/ft, while the Lotena formation has an equivalent pressure ranging from 0.42-0.48 psi/ft.The Intracalovian unconformity, located between Lotena and Punta Rosada formations could explain the abrupt changes in pore pressures.

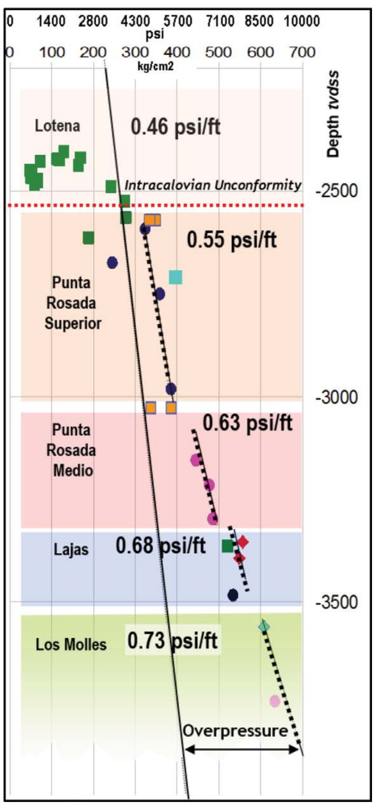


Figure 9. Equivalent pressures in Punta Rosada Lajas from MFO and DFIT tests

## 1D PORE PRESSURE MODELING

### Overpressure mechanism

A critical step in pore pressure modeling is the identification of the overpressure mechanisms, Grauls (1999) details the typical overpressure mechanisms. From them, fluid expansion (Hedberg, 1974) and lateral transfer (Traugott, 1996) seem to be the more likely mechanisms in Punta Rosada, Lajas and Los Molles formations (the first two represent the main tight gas targets). Fluid expansion probably occurred during the second hydrocarbon source rock maturation pulse and the hydrocarbon cracking, trapped in the reservoir rock (Figure 5)The temperature could be influencing this fluid expansion, although in minor extent (reservoir depth from 3000-4000m). Lateral transfer is believed to occur when communicating the source rock of Los Molles with the reservoir rock though a complex fault system, mainly present in the center part of the block. Natural fractures are limited.

Fluid expansion and lateral transfer can be treated as type II overpressure mechanisms. They can be modeled using the concept of unloading curve, as explained by Bowers (1995). If HC generation is present then it is expected the presence of an overpressurized source rock while lateral transfer can be explained though the presence of faults acting as flow paths.

The overpressure model assumes that those zones with lower permeability will retain most of the overpressure while those intervals with higher permeability will tend to have a lower overpressure. Since Rio Neuquen is a tight play, low permeabilities are assured, which favors the overpressure preservation; furthermore, the source rock of Los Molles hashigh TOC and kerogen, supporting the evidences of fluid expansion.

### Effective stress-velocity transforms

A series of effective stress-velocity transforms were built to understand the overpressure type. A useful tool for performing this analysis was the implementation of effective stress-velocity type curves (Figure 10), using effective stress-velocity transforms from literature and other from the area. This type-curve analysis showed that pressure data is located far from the loading path (virgin curve) and close to unloading type-curves. Velocity-density crossplots were also used to validate the unloading profile (Bowers, 2001). The analysis was performed at well-scale (i.e. along the whole interval) showing some unloading behavior (Figure 11), although a similar analysis applied only to the control points was non-conclusive.

Type I overpressure is unlikely, as per type curve analysis and velocity-density crossplot. This result is consistent with the age of the reservoir (Jurassic) and compaction of the sediments (rockporositiesare expected in the lower ranges, from 4 to 10%). This kind of rocks are more prone to type-II overpressure, including not only hydrocarbon generation and fluid expansion but alsodiagenesis, tectonics, etc.

Loading and unloading curvesfor type-II overpressure werecalibrated withavailable data in normally and abnormally pressurized intervals. Both curves used the multi-variable effective stress-velocity equationproposed by Sayers (2003), which incorporates not only the velocities but also the effects of Porosity and VCL in the pore pressure transform, as presented in Equation 3. Notethe first three parameters of the equation are equivalent to Vo in the loading and unloading expressions of Bowers equations 1 and 2.

$$\boldsymbol{v = a1 - a2\varphi - a3C + a4\,(Sv - P)^{a5}} \qquad \text{Equation3}$$

Where: $a_1$ is the Initial velocity coefficient (ft/s), $a_2$ is a Porosity coefficient (ft/s), $a_3$ is a Lithology coefficient (ft/s), $a_4$ is the Effective stress coefficient, $a_5$ if the Effective stress exponent, $S_v$ is the Vertical stress (psi) and $P_p$ the Pore pressure (psi).

The main challenge when modeling effective stresses from unloading curves is the estimation of the maximum effective stress. As will be shown later, this parameter is highly variable along the Punta Rosada-Lajas interval, due to the very different burial depths. The last required the construction of a depth-dependent unloading curve where regression analysis provided the minimum error solution and best fit coefficients forequations 1, 2 and 3.

**Stress sensitive behavior**

Pore pressure prediction in tight rocks and source rocks (typically older) is not as reliable and common as in many young sediments, however, the stress sensitive nature of the rock is the real constraintfor using seismic or acoustic velocities in effective stress-velocity solutions (Huffman 2000). In Rio Neuquen, the ultrasonic velocities from lab tests showed a reservoir rock very sensitive to stresses which validates the presence of an unloading zone. The magnitudes of these velocities are the real challenge, as they could be affected by other variables rather than just effective stresses. Some of these variables, like lithology and clay content, were accounted for in this study, others, such as the rock type or gas presence were not considered yet. Based on the laboratory tests results and the solution to the effective-stress velocity transform it is assumed that most of the velocity response comes from the effective stress of the rock.This assumption was necessary for the 3D pore pressure modeling as the seismic inversion didn’t produce a reliable estimate for facies and lithologies. Furthermore, the VCL and PHIT analysis showed a minor impact in velocities than the stresses.

### Type-curve analysis and velocity-density crossplots

The type-curve analysis was used to match actual data against different loading paths. The loading paths were extracted from both literature and local models, as presented in Figure 10. None of the pressure points in Punta Rosada-Lajas (red and blue dots) fall above the reference loading curves. This suggest a possible type-II overpressure mechanism. Note that actual pressures are like those predicted by the unloading reference curves. The last agrees with the presence of a source rock below (Los Molles formation) and the location of the interest zone inside the hydrocarbon generation window, probably leading to a fluid expansion mechanism responsible for the unloading.

Figure 11show the velocity-density crossplot, filtering the data inside the reservoir zones. A typical unloading response (black arrow) is evident (considering previous assumptions in the velocity response),showing a clear increase in slowness (decrease in velocity) for almost constant density values. This response is attributed once again to type-II overpressure mechanisms, although some gas effect could be influencing the readings (Han 2004).

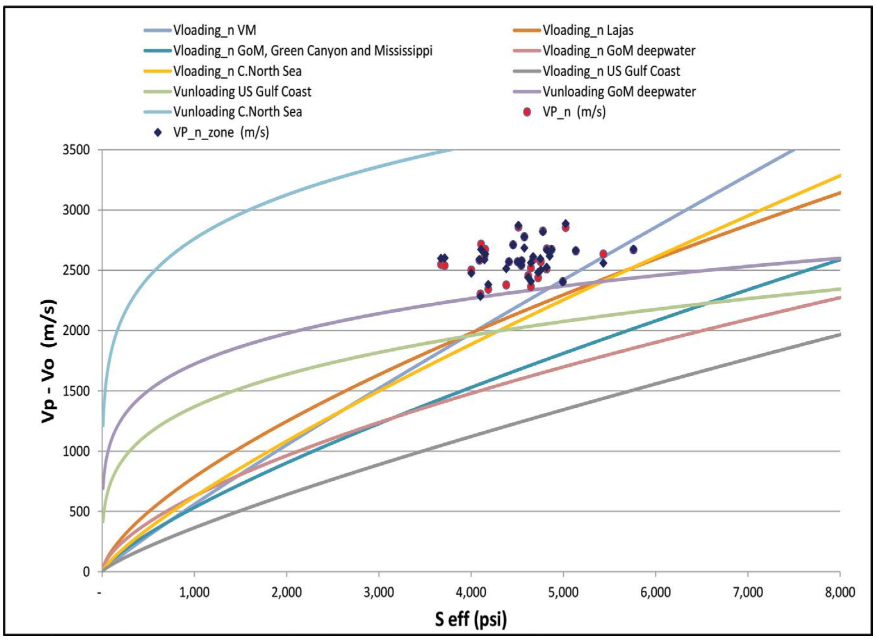


Figure 10. Type curve analysis for the effective stress-velocity crossplot – Loading and Unloading paths

## INITIAL PORE PRESSURE MODEL

### PP approach for the loading/unloading curves

Loading and unloading curves are modeled by separating the normal pressure (purple squares)

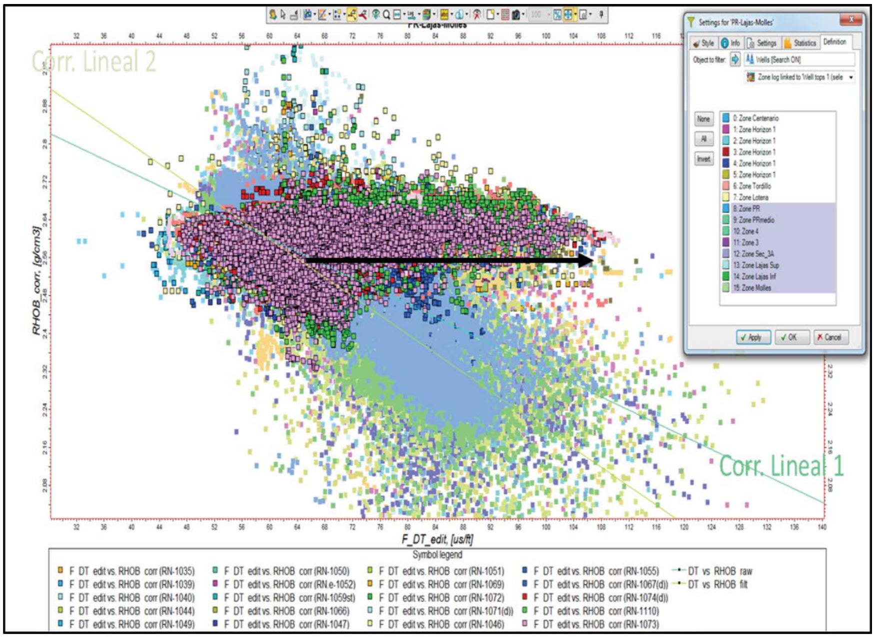


Figure 11. Density-Slowness Crossplot (filtered in the reservoir zones)

from the abnormal pressure readings (blue diamonds). Since only type II mechanism is expected in Punta Rosada-Lajas,the loading curve will represent the normally pressurized intervals above such formations. Since no type I mechanism is expected inside the reservoir section,the effective stress can be easily estimated using the model presented inFigure 12, where the available pressure readings match both the loading (blue curve) and unloading curve (gray curve).

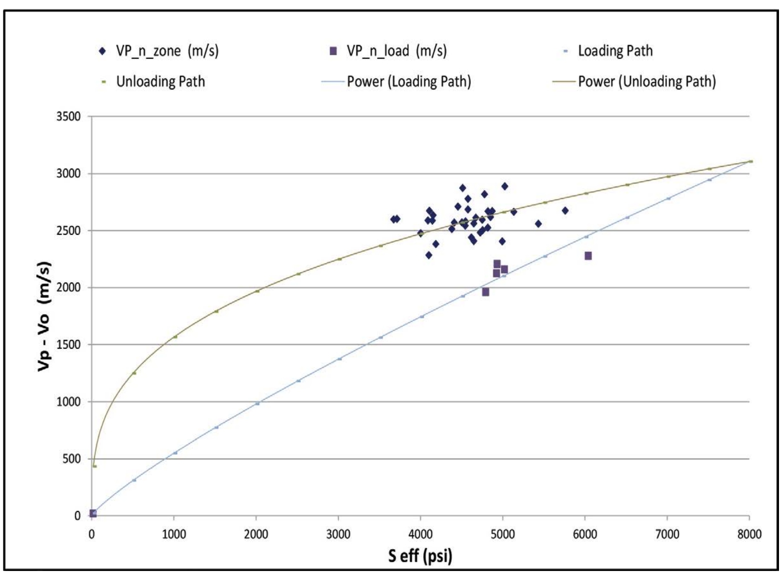


Figure 12. Preliminary loading and unloading curves for the entire well

### Laboratory tests

Ultrasonic velocities measured in laboratory samples subject to Triaxial compressionshows that almost all the samples present a stress sensitive behavior. These results suggest that the velocity reversals are strongly affected by loading and unloading processes. Although ultrasonic velocities from lab response could be different from that of the log response (due to frequency, scale and confinement conditions) they validate the initial assumption of a highly stress sensitive formation.

### Other Factors affecting the velocity response

Initial velocity, clay content, porosity and effective stress were had into account when solving theEquation 3. The final pore pressure solution improved when using VCL and Porosity, but most of the weight fell in the effective stress and its coefficients a4 and a5 in Equation 3. Due to this and the lack of lithology and porosity cubes for the 3D approach, it was created a separated and simplified model for the 3D pore pressure modeling, which include the coefficients a1, a4, a5, and the variables velocity and Seff max (i.e. the original Bowers solution for unloading). The 1D approach, however, included all the coefficients (a1, a2, a3, a4, a5) and variables (p-velocity, Seff-max, VCL and porosity) of Equation 3.

Fluid effects were not considered in this study and must be accounted separately, through appropriated methodologies (e.g. removal of gas effect through QC flags, log modeling, fluid substitution, etc).

## FINAL PORE PRESSURE MODEL

Two different pore pressure models were built. The first one based entirely in Velocities and Seff-max (Bowers, 1995) and the second one using the multivariable approach (Sayers, 2003) with variable Seff-max. As mentioned before, the “maximum effective stress” parameter (Seff-max) is all excepting constant, varying a lot along the reservoir zone. This variation is attributed to the important vertical thickness of Punta Rosada-Lajas formations (the reservoir section) varying from 915 to 2186 m in the deepest zones and averaging 1550 m along the block, requiring a depth dependent unloading curve (with variable Seff-max). A detailed analysis showed that a “maximum effective stress” parameter variable in depth is not only physically consistent but produces a better estimation of actual pressures, reducing the mathematical error in the solution of Equation 2. The regression analysis of the Equation 2 and Equation 3 with constant and variable Seff-max showed that a depth-dependent Seff-max improved the pore pressure solution notably.The variable Seff-max parameter is presented as different unloading curves in Figure 13, where most of the control points are located.

## 1D Pore pressure model profiles

The final pore pressure model was well constrained thanks to the good amount of well data and pressure measurements. Figure 14show the calibrated pore pressure profiles for different wells (pressures and gradients in the last two tracks). Note the general good match between the final model (dark blue curve) and the real measurements (red dots). The blocked shape of the pore pressure curves is consequence of the grid, since all the analysis was performed over a structural grid. There is also presented the pore pressure model using a constant Seff-max (light blue curve) and the pore pressure model using only the loading (turquoise curve). The figures also show the used MW (brown line) and ECD (pink line).

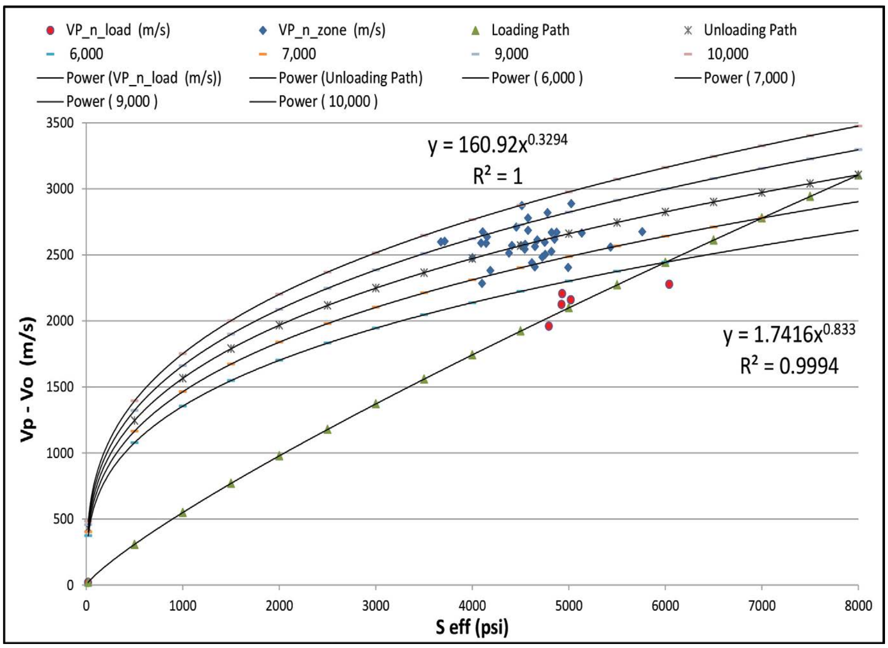


Figure 13. Final Effective stress-velocity transform. Loading and variable Unloading curves

Despitethe assumptions, the model matches very well the pressure readings in 17 of 21 wells. There are several hypothesis for explaining the low confidence in the predictions in the remaining four wells: first one is the lithological effect, which is particularly evident in Lajas formation, where a thicker sequence of cleaner sandstone deposits could be affectingthe effective-stress velocity response, much more if compared with the shale/sand levels of Punta Rosada formation; the second one is the representativeness of interval velocities from seismic inversion, this is the case of some wells where there is an important mismatch between the velocities from seismic inversion and the filtered acoustic logs; the last one is timing, seismic, logging and pressures testing did not occur at the same time, so velocity response could not be measuring the real effective stresses during the pressure tests (this effect, however, is considered negligible in Rio Neuquen). If the control points were affected by depletion then those pressure points were removed from the analysis.

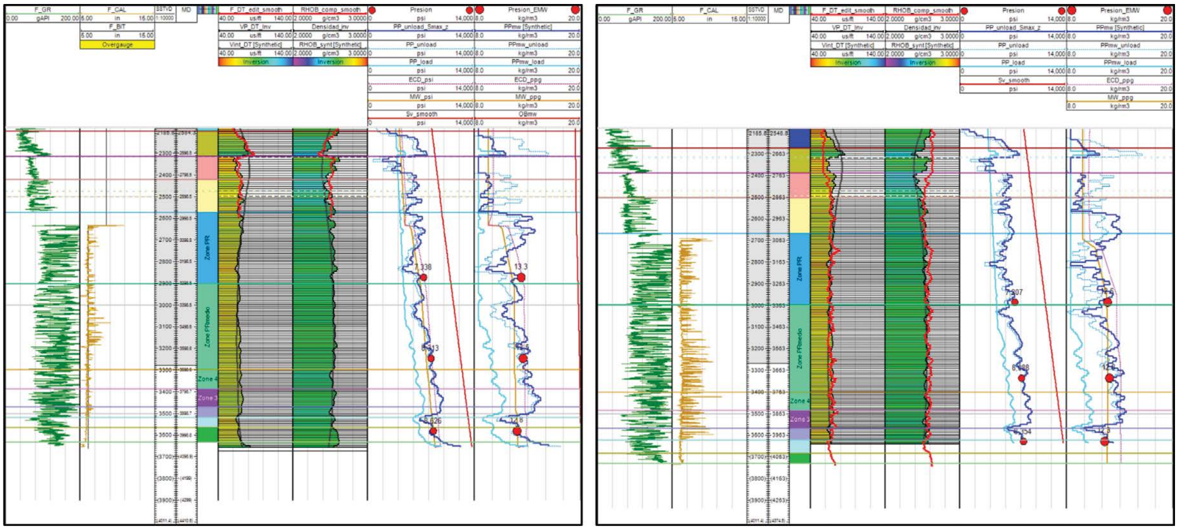

Figure 14. Pore pressure model well 1& 2- Punta Rosada-Lajas

A blind test analysis was performed in the well22, probing the validity of the final pore pressure model. The results presented in Figure 15 shows the excellent match between the modeled pressures and the interpreted values from DFIT analysis in Punta Rosada Superior, including two interpretations: 5742 psi to 3114 m and 5608 psi to 3154 m (red dots inside the blue rectangle). Note that both readings adjust very well to the model (dark blue curves in tracks 8 and 9).

The overall model will be improved once the lithology, porosity and gas effects are used as inputs in the 3D cube. In general, main differences between the modeled pore pressures and the real ones are associated to differences between the expected velocities from seismic and the actual velocities.

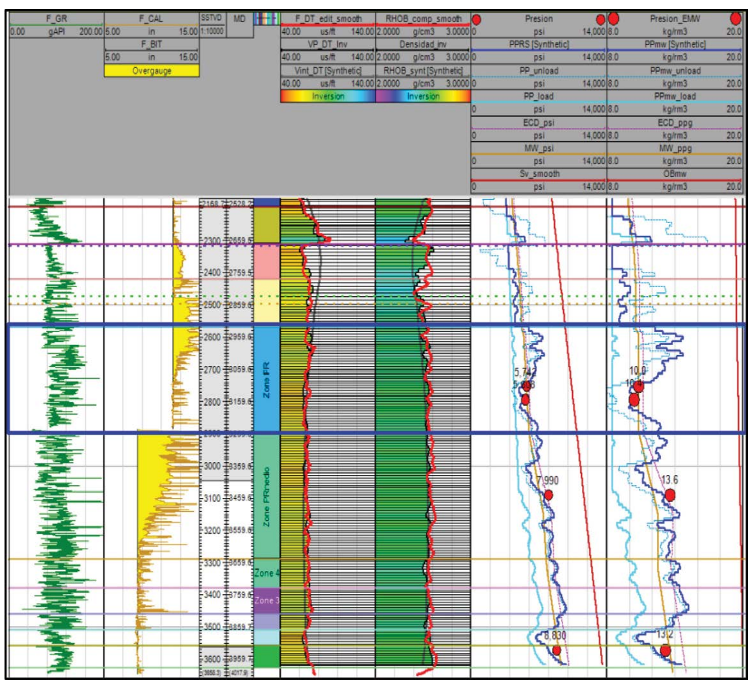

Figure 15. Blind test well 22

## 3D PORE PRESSURE MODEL

The pore pressure cube was computed using the 1D pore pressure model. Input data includes the structural model, velocities and density from seismic inversion. Coefficients and otherparameters were brought from the 1D model, which used as input both the well logs and the interval velocities from seismic inversion.

The final 3D model was validated against data from 21 wells in Punta Rosada-Lajas (abnormal pressures) and 10 wells in Lotena formation (where normal pressures exist). The average pre-production pressure gradient in the reservoir zone ranges from 0.58-0.70 psi/ft. In tight reservoirs, transmissibility is so low that the radius of drainage is expected to be close to the well, thus making the interference between wells unlikely. The last would explain why despite the timing difference between the well logging (acoustic or VSP) and seismic acquisition, both measurements are assumed to be representative of the pre-production stage. The last, however, could not be the case in Lajas formation, whose higher transmissibility could affect the original pressures between nearby wells. This and the factors described before would explain most of the differences between the pore pressure prediction and the actual pressures in Lajas, especially in the four wells mentioned in the 1D pore pressure section.

Figure 16 shows a cross section for the pore pressure gradient cube. Note the higher pressures represented in red color in the bottom of the seismic, corresponding to Los Molles formation (the

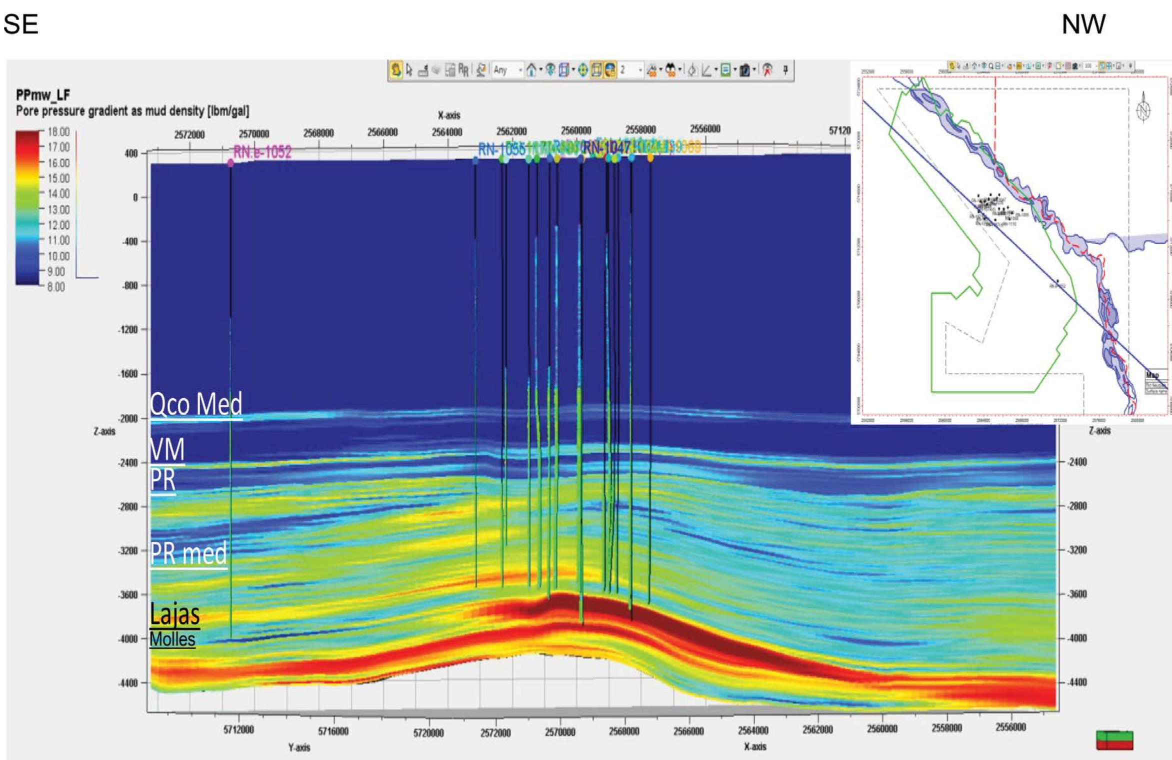


Figure 16. Modeled pore pressure gradient, Inline SE-NW including Los Molles formation

source rock, whose pore pressures are not calibrated) while Lajas formation is just above. There are two minor pore pressure anomalies in Quintuco Medio and Vaca Muerta but the major pore pressure ramp starts in Punta Rosada formation, increasing downwards to Los Molles formation. Note the bigger pore pressure anomaly is in the center of the structure in the anticline high. This zone has two characteristics: in first place the presence of several normal faults resulting of older tectonic events; in second place the major thickness of Los Molles formation, where pore pressures are expected to be higher the same as the hydrocarbon generation volumes.

There is also an important pore pressure anomaly in Punta Rosada Medio-Inferior with some regressions in Punta Rosada medio and the transition between Punta Rosada Inferior and Lajas Superior. Finally, the figure shows the abrupt change in pore pressures on Punta Rosada Superior, pointing out to the location of the Intracalovian unconformity.

**Overburden and structural model considerations**

Other key aspects of the 3D model include the consideration of the topography effects and the inclusion of rock density and overburden above the seismic datum. The construction of a grid is optional, although it can help to perform local analysis, applying advanced filtering, implement models with greater complexity (multi-variable) and reduce the size of the seismic survey.

The advantage of including the topography and the laterally variable seismic attributes (as velocities and density from AVO/AVAZ inversion), is among others, the ability to calculate a laterally variable overburden stress which is a first other parameter in pore pressure calculation. This effect is particularly notable under the presence of abrupt surface reliefs such as ranges, canyons or cliffs. Seismic and structural data must be migrated to depth domain.

Due to the poor quality of the density cube from the seismic inversion it was decided to build a density cube from well logs using local correlations derived from the P-wave. This density cube was used to estimate the final overburden stress for the block, varying from 8,600 to 18,200 psi in Punta Rosada-Lajas (mean 13,400 psi). Average overburden stress gradient ranges from 1.03-1.04 psi/ft (2411 g/l – 2434 g/l). In the upper formations (including Quintuco-Vaca Muerta) the average overburden stress gradient is 1.01 psi/ft (2364 g/l).

**Pore pressure model – parameter considerations**

The final pore pressure model coefficients are result of the regression analysis, becoming the best mathematical solution of Equation 2 and Equation 3. The coefficients were assumed constant for the entire block. A different approach would be estimating variable coefficients along the block, mapping the lateral variability and uncertainties. This approach is more appropriated when input data is widely distributed across the block;in Rio Neuquen, however, well data is concentrated in central part, so that pore pressure coefficients were inverted and kept constant for both loading and unloading. Only the maximum effective stress parameter was considered variable.

## GEOPRESSURES AND PETROLEUM SYSTEM

Pore pressure cube allowed us to visualize the spatial distribution of the overpressure anomaly, identifying the areas of the field where the entire reservoir column is overpressurized and sectors where the top of the overpressurized zone start to decrease (Figure 17). In this way it was possible to delimit the development area and sectorize it in zones with different production potential. Additionally, new exploratory prospects were identified, based on the overpressure anomaly.

The overpressure distribution shows a strong relationship with both the underlying thickness of Los Molles formation and the prevalent faulting systems, especially with those faults that connect the entirecolumn of Cuyo Group (Figure 17). That situation reinforces the hypothesis of oil and gas migration through faults.

Another type of pressure control is the stratigraphic one, being related to the presence of unconformities and flooding surfaces, which would have acted as local seals (Cumella et. al., 2005), containing the oil from the first expulsion period and later cracked to gas during the second pulse. The pore pressure cube shows a kind of "overpressure pockets" which are limited by faults and these surfaces (Figure 17).

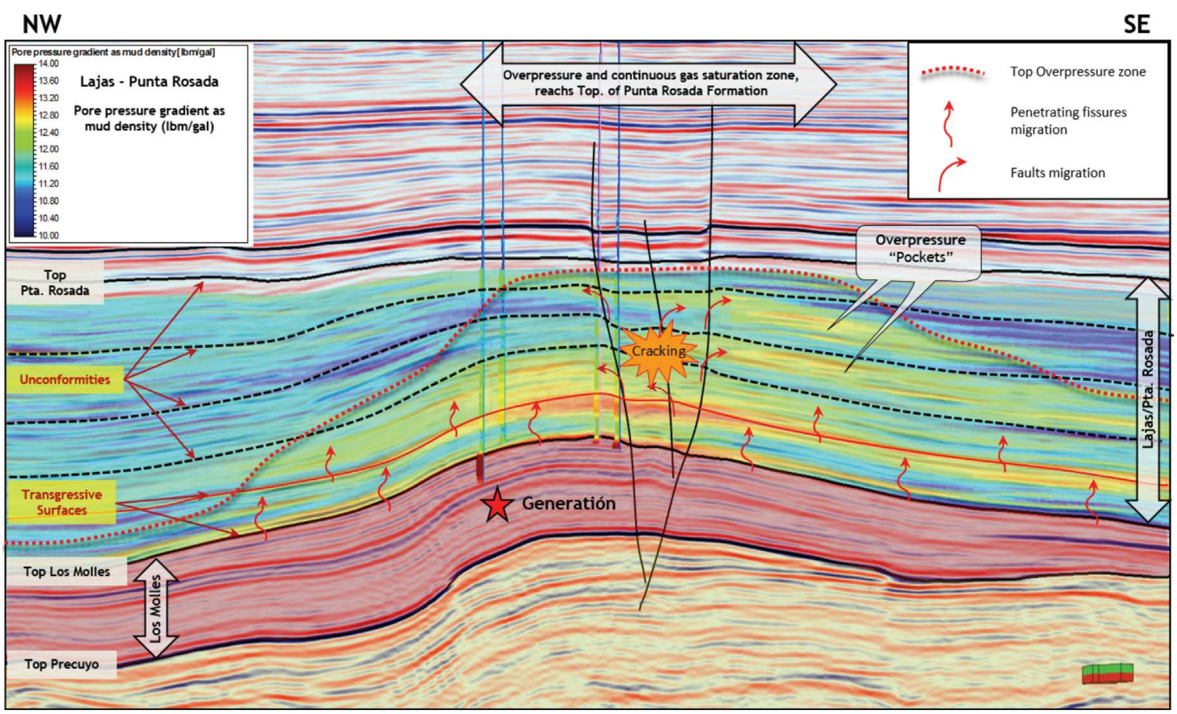


Figure 17. Seismic section with calculated Pore Pressure Gradient

The unloading analysis can also explain the presence of unconformities. As previously stated, maximum effective stress was variable along the reservoir interval. A unique Seff-max value, was found at 8,000 psi (after the regression analysis). This value is bigger than the theoretical value of 7600 psi that would be expected in the middle part of the reservoir zone. This +400-psi difference could be explained assuming the loss of sediments, for example, during an erosional process. This observation matches the geology, which suggest the presence of some unconformities inside the reservoir interval. The thickness of this hiatus was estimated in 210 m, after inverting the equivalent burial depth required to achieve a Seff-max of 8,000 psi(no rock compaction considered).

Finally, pore pressures showed some correlation with well productivity for most of the completed intervals (excepting Lajas), as showed by the different PLT readings in Figure 18. Thus,the pressure anomaliespredicted by the pore pressure cube couldbe used not only for well location and field development plan but also for designing better completion strategies.

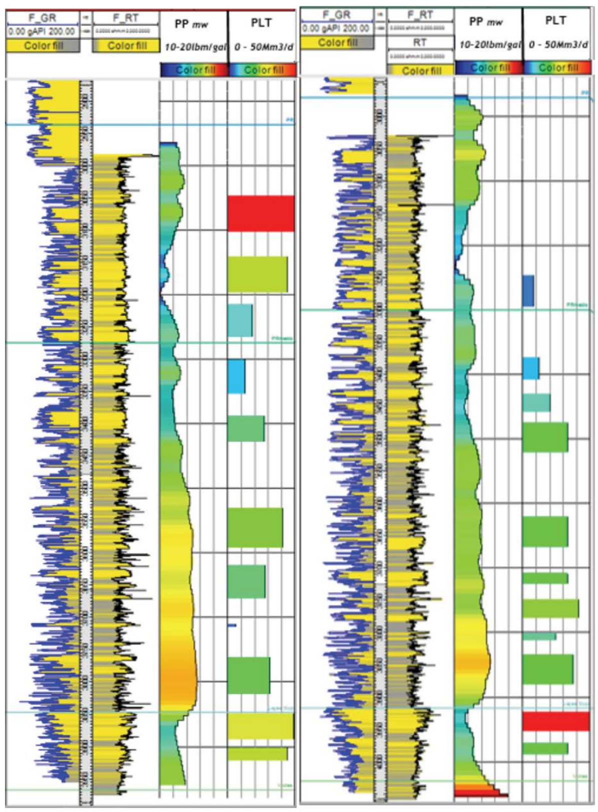


**Figure 18. Wells showing the Estimated Pore Pressures and the PLTvalues**

## OTHER CONSIDERATIONS

### Lithological effect considerations

Lithology effect was not considered in the 3D pore pressure model due to the absence of any lithocube or 3D petrophysical model but it was considered in the 1D pore pressure model, producing superior results. The final pore pressure cube was smoothed using three iterations to clean the high and low velocity intervals formed by cleaner sandstones and shales respectively. This procedure improved the vertical continuity in the model, impacting positively the pore pressure predictions.

### Velocity field considerations from PSDM and AVO inversion

PSDM velocities exhibit a velocity anomaly at the top of Punta Rosada formation, thereafter the velocity is completely unchanged, almost flat, differing substantially from the acoustic logs. Velocities from AVO inversion, on the other hand, reproduce very well the filtered acoustic logs along this formation. Due to this, final pore pressure model from PSDM velocities did not reflect the actual pressures, while the model built from the interval velocities of AVO inversionwas more consistent, especially in Vaca Muerta and Punta Rosada superior. The prediction error was less than 10% for all the points.

## CONCLUSIONS

Type curve analysis for loading/unloading, velocity-density crossplot and UV velocities from triaxial laboratory tests suggest the presence of stress sensitive rocks. All of them show evidences of possible unloading processes in the reservoir rocks.

It is likely that Punta Rosada-Lajas and Los Mollesformations are experiencing multiple overpressure mechanisms including lateral transfer across the fault systems and fluid expansion from hydrocarbon generation, these mechanisms correspond to type-II overpressure mechanisms.

The effective stress seems to play an active role in both seismic and acoustic velocities of Punta Rosada-Lajas. Gas effects could be affecting these velocities but they were not accounted for in this study. Lithological and porosity effects are less evident in the intervals used as control points, as suggested by the multi-variable regression analysis.

PSDM velocities exhibit a velocity anomaly at the top of Punta Rosada formation, thereafter the velocity is completely unchanged, almost flat, differing substantially from the acoustic logs. Velocities from AVO inversion, on the other hand, reproduce very well the filtered acoustic logs. Final pore pressure model built from the PSDM velocities does not reflect the actual pressures.

The pore pressure model built from the interval velocities of the AVO simultaneous inversion improves the representation of the pore pressure anomalies in Vaca Muerta and Punta Rosada superior. In the reservoir zone, the model approaches very well to the control points, reaching a maximum error of 10%.

The use of the maximum effective stress variable with depth Seff-max_z enhances the pore pressure accuracy, so that the pore pressure model along Punta Rosada-Lajas is based in the implementation of effective stress-velocity transforms with variable unloading curves. Other parameters and coefficients are set as constant along the Rio Neuquen area.

There is a sudden change in pore pressures between Lotena and Punta Rosada Superior. This change coincides with the presence of a discordant surface. There is other hiatus like this inside the Punta Rosada-Lajas sequence, all of them affecting the pore pressure model.

The mean value for Seff-max is 8,000 psi, suggesting the presence of a hiatusthat could be greater than 210 m.This finding shows that Seff-max concept can be used to understand the geological evolution and structural restoration of the block.

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