USE OF ACOUSTIC IMPEDANCE IN THE EXPLORATION AND DEVELOPMENT OF A GAS FIELD: AGUADA PICHANA NORTE CASE STUDY

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Abstract

El yacimiento gasífero de Aguada Pichana se encuentra en la Cueca Neuquina. El reservorio principal es la formación Mulichinco (Cretácico Inferior) formada por arenas de permeabilidad entre media y baja.

El desarrollo del campo reposa en la identificación de *"sweet spots"* así como en la síntesis geológica. La hipótesis subyacente es que bajas impedancias corresponden a altas porosidades. El aumento local en la permeabilidad depende de la distribución de facies (cuyo pronóstico resulta del modelo sedimentario) y de procesos diagenéticos.

La formación Mulichinco presenta una estrecha relación entre impedancia acústica y porosidad. Por esta razón, la inversión acústica es una herramienta importante en la caracterización del reservorio en Total Austral. La inversión acústica se realiza *in-house* de modo que el modelo inicial es actualizado a medida que avanza la campaña de perforación. El proyecto actual comprende un área de 1600 km^2 de sísmica 3D con más de 100 pozos en el modelo inicial.

Este método fue implementado con propósito exploratorio en el norte del bloque de Aguada Pichana. Se definió un prospecto usando la impedancia como guía en la construcción del modelo geológico. El primer pozo, APN.x-1, perforado en diciembre de 2004, probó excelente productividad en el *Upper* Mulichinco. Tres pozos adicionales también confirmaron buena productividad y permitieron delinear y evaluar el área.

El desarrollo de la parte este de APN (Fase 1) está en progreso actualmente. Se espera el comienzo del desarrollo de la zona oeste para 2009.

Keywords: Seismic acoustic inversion, sweet spots, porosity, permeability.

1. INTRODUCTION

1.1 Field Characterization

Aguada Pichana block is located in Neuquén Basin in the central-west part of Argentina (Fig.1). It is the second largest gas accumulation in the country with an estimated daily production of around 14Mm^3.The field was discovered in 1970 by YPF and, in 1994, Total Austral took the operatorship in a JV with Repsol YPF, Pan American Energy and Wintershall. AP Main production started in 1996 reaching a 2nd phase at full plant capacity (14MSm^3/d) in 2004.

The Aguada Pichana field (including AP Main and AP Norte) extends over the eastern flank of the Chihuido Anticline and follows the same trend of Sierra Chata and Aguada de la Arena fields, situated to the North and North-East of AP block.

Aguada Pichana Norte sector, the subject of this study, is delimited to the north by Sierra Chata field and to the south by AP Main field (Figure 2).

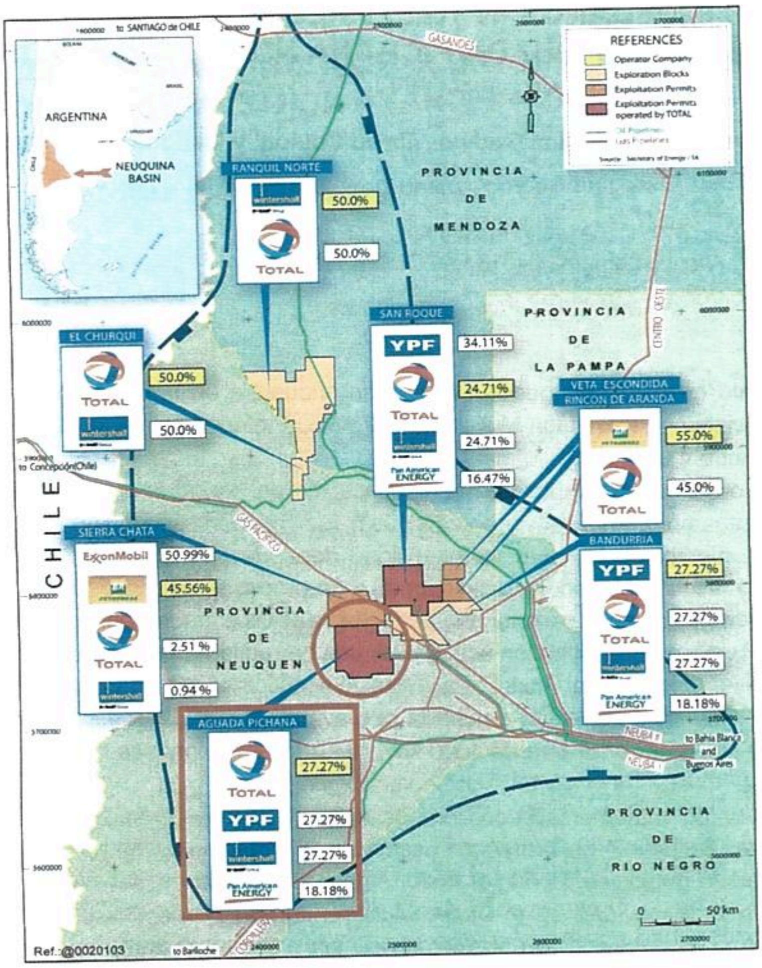

Figure 1. AP block in Neuquén Basin in Argentina.

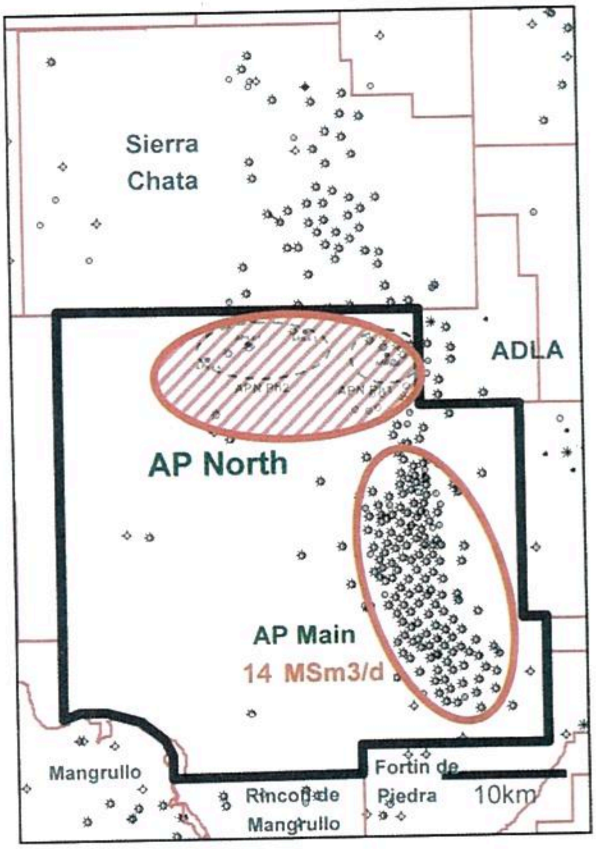

Figure 2. Main fields in AP area.

The main reservoir in AP block is the Mulichinco Formation. It is found 1600 m SS and its thickness ranges between 150 m and 250 m thickening towards the NW (Figure 3). It consists of early Cretaceous gas and condensate bearing sandstones of medium to low permeability. Permeability is the main issue and hydraulic fractures stimulation is needed to produce in all wells.

The trapping mechanism for the Mulichinco Formation sandstones (main objective), is a combination of stratigraphic and structural trap. It is closed by a regional gas-water contact downdip to the east and a progressive degradation of reservoir quality (possibly related to the different intensities of diagenetic processes that affected the rock) to the west (Figure 4).

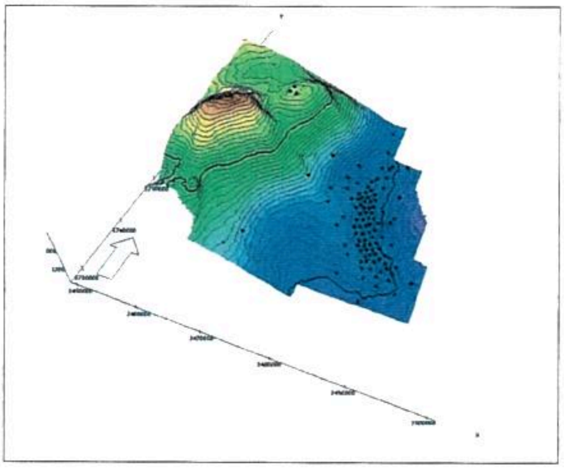

Figure 3. Upper Mulichinco Structural map. Aguada Pichada field lies in the eastern flanck of Chihuido anticline.

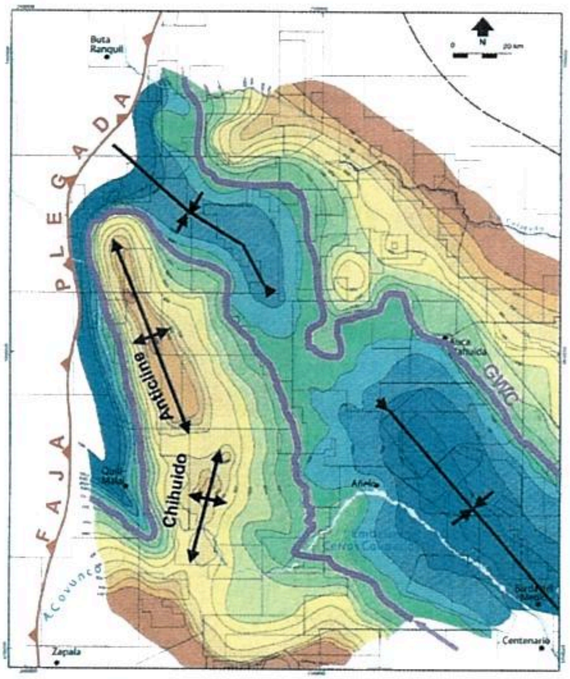

Figure 4. Mulichinco Structural and Stratigraphic trap.

The Mulichinco and the overlying Agrio Formations are interpreted as a second order depositional cycle: the Mulichinco Fm. corresponds to the lowstand and transgressive system track while Agrio Fm. is associated to the highstand (Legarreta *et al.,* 1989).

In AP block, the Mulichinco Formation is divided in three 3rd order sequences, namely a Lower, Middle and Upper Mulichinco members, separated by third order sequence boundaries (Figure 5).

The Formation began with an eolian dune system above a second order sequence boundary developped over the carbonate platform of Quintuco Formation.

A third order erosional surface separates the lower and middle members of Mulichinco Formation.

Above this surface, a fluvial system began to overlap with a clear tidal influence in the northern area c the block.

Tidal and estuarine channels in a marsh environment caused minor erosion over the underlyin deposits and developped a new third order sequence boundary, marking the beginning of marin transgression of the upper Mulichinco Formation.

Transgressive limestones overly the Mulichinco Formation.

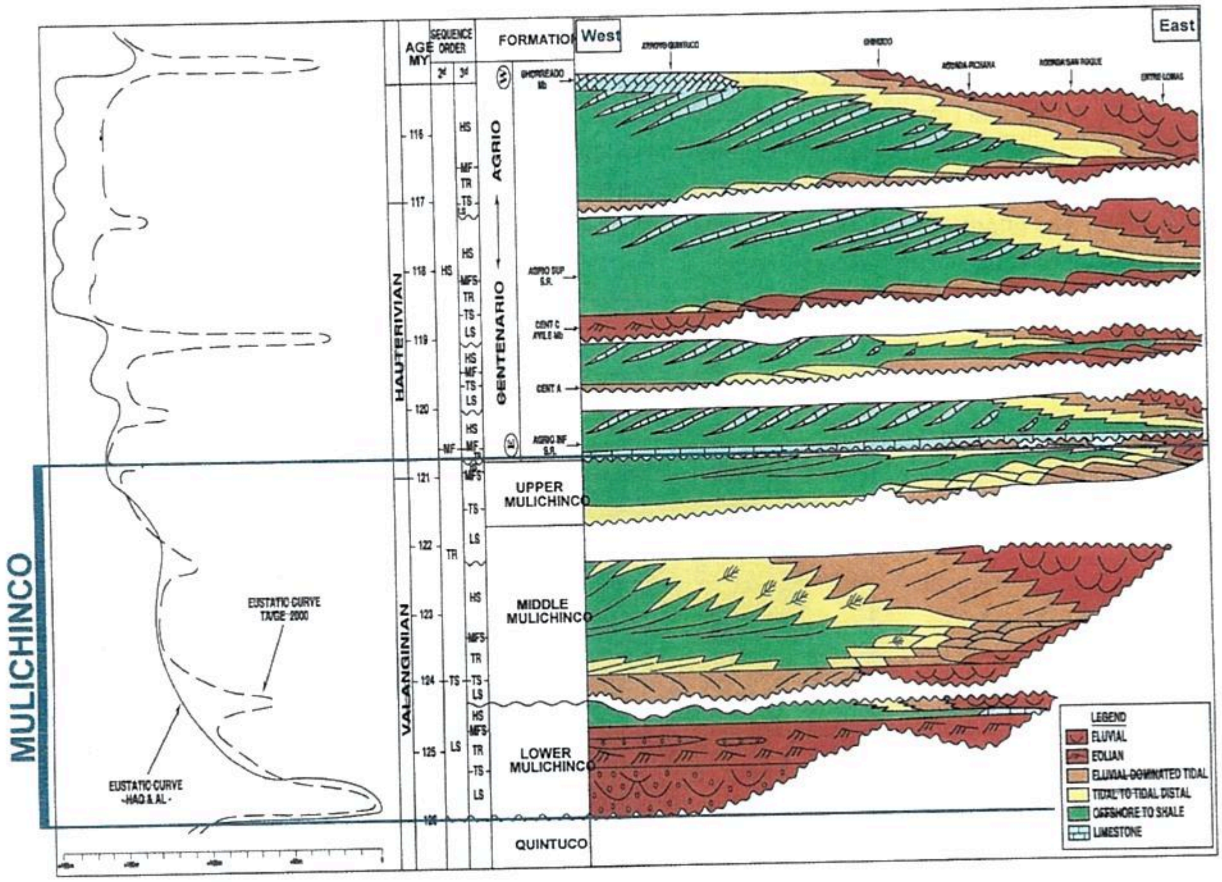

Figure 5. Mulichinco stratigraphical interpretation.

1.2 Geophysical Data

3D Seismic surveys were recorded in the period going from 1995 to 2005 with various layouts and acquisition parameters. AP area had been previously covered by 2D seismic (2100 km of seismic lines from various vintages ranging from 1970 to 1996).

In 2001 a 3D survey was shot in APN sector (349 km²) and merged after migration with Sierra Chata and Aguada de la Arena surveys. An inversion was performed in-house by Total Austral on this 3D merge and moreover 2D data was reprocessed (in order to transform the different seismic vintages into a homogeneous set of data, compatible as much as possible with the APN 3D seismic) and inverted.

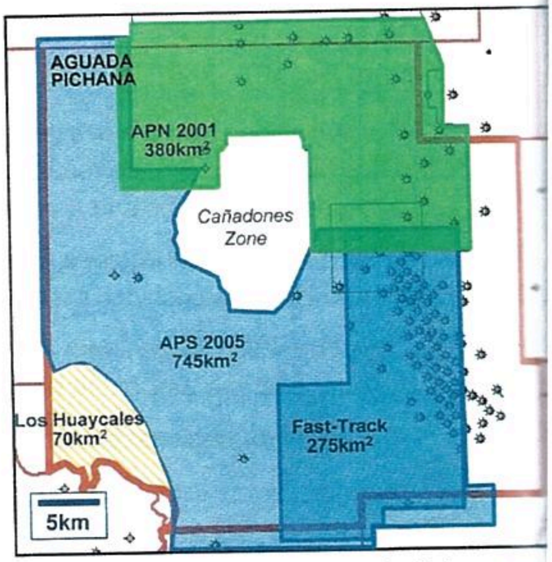

Figure 6. 3D Seismic data in Aguada Pichana are

In the South, the development of AP-Main sector continued based on 2D inversion until the 3D seismic survey AP Sur was acquired in 2005. In 2006, the joint processing of all surveys was done - except ADLA because records were unavailable (Figure 6). Strong efforts were devoted to improve the Mulichinco reservoir character preserving amplitudes and increasing the effective bandwidth.

2. SEISMIC ACOUSTIC INVERSION

Post-stack inversion was made using Hampson-Russell's model based algorithm. Tests have been carried out to validate seismic amplitude compensation parameters, inversion wavelet, initial model construction and quality controls, iterations number and scaler[1] 'determination. In particular a 20/30 Hz low-pass filter was applied to the initial acoustic impedance model.

Aguada Pichana inversion database contains more than 140 wells located within the area covered by 3D seismic. Logs were carefully verified, edited if necessary where calliper deviated from expected values and filtered with a 90/100 Hz high-cut operator. Wells with non-reliable sonic or density curves were left out of the initial model. In some wells with strong calliper issues density logs were unusable, thus a synthetic density was computed from the sonic log using Gardner equation calibrated with neighbouring wells. However, it should be noted that weak well to seismic correlation coefficient was not considered as a criterion to leave a well out of the model since the low frequency content can't be discarded by means of seismic information only.

The initial model is an inverse square interpolation of validated impedance logs guided by the top and base Mulichinco horizons. There are 132 wells inside the model. It has a 2ms blocky format, conformable stratigraphy between the horizons and it was filtered with a 20/30 Hz low-pass operator after interpolation. This model was controlled for bull's eyes extracting the acoustic impedance average at various intervals (applying first a 10/15 Hz low-pass filter). Some suspected well log problems were confirmed by this manner and some of them were left out in the final version.

PSTM rms-amplitude maps extracted at windows around the top reservoir horizon showed variations up to 500% related to surface conditions, acquisition source (vibrators or dynamite), and non uniform energy dissipation during wavefield propagation. Therefore, prior to inversion, an amplitude compensation coefficient had to be defined. Several tests were done in order to select a computation window. The amplitude compensation should be done with large windows where energy normally stabilises by randomness considerations. However, several constraints exist such as high energy events of underlying Quintuco reefs which might contaminate the compensation factor, low S/N at the shallow part of the section and lateral variation of Avile formation and top Centenario response. The compromise was fulfilled using a 600ms window around the top of the reservoir.

Wavelet statistics have been performed over 70 wells showing a quite stable bandwidth properly matched by a 7-16-80-90 Hz band-pass and a plane phase average of 10 degrees with a standard deviation of 30 degrees. Extraction was made with Landmark's Syntool using a 5x5 traces region around each well, a 128ms length wavelet and an extraction window of approximately 400ms (at least 3 times the wavelet length). The extraction was done by autocorrelation and a constant phase has been set by correlation in an approximately 120ms window around the reservoir. Inversion has also been tested using a time averaged wavelet and a synthetic band-pass showing negligible difference compared to the inversion uncertainty.

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[1] The scaler is related to the inversion dynamics around the inicial model. Smaller scaler valules will allow for bigger deviations from the input initial model.

The inversion algorithm is the hard constrained (45%) model based inversion with 15 iterations. 2ms average block size, 5% pre-whitening, 7-16-80-90 Hz band-pass, 128ms length and 2ms sampled wavelet and a scaler P_2=45. Scaler determination was done mapping the optimum scaler at each well. The adopted solution is acceptable as a compromise and there is no qualitative difference which might mislead the geological model construction. The Inversion uncertainty in areas with good well density is 500 m/s·g/cc.

Aguada Pichana vertical resolution limit is ~ 18 m which is in the same range or higher than the reservoir thickness. The presence of interfered reflections everywhere implies that thickness dependant amplitude variations exist, but traditional tuning analysis on the horizons is not suitable in AP context to measure tuned areas due to the complexity of the reflection pattern. We have done tests to measure the inversion error with several synthetic earth models and there was no significant effect associated with the tuned amplitudes. We haven't found any problem with the inversion of pairs or groups of tuned reflectors. On the other hand we have numerous examples where tuned sandstone beds were predicted with rather good results. In practice, the inversion has proven to be robust to predict with reasonable accuracy the acoustic impedance in numerous wells where tuned amplitudes were confirmed by reflection coefficients logs.

3. METHOD

3.1 Geological model construction

Aguada Pichana Norte field potential evaluation was done based on Aguada Pichana Norte and Sierra Chata geological model. The geological model integrates the regional knowledge, the petrophysical interpretations, core analysis and sediment descriptions using acoustic impedance to guide the construction.

The geological model construction (Figure 7) starts by drawing the geological facies maps. Impedance is used to shape each level honoring well data. Figure 8 shows an example of interpretation given to observed features on seismic impedance section in terms of facies (tidal bars, tidal channels and the associated fluvial facies feeding the system). In APN field, 8 rock types with specific reservoir properties were defined (Figure 9). Each geological facies is associated with certain ensemble of rock types. The rock type maps are then derived honoring the dominant rock type at each well and using impedance maps as spatial-guide and facies boundaries as constraints. Finally, porosity and permeability maps are derived from rock type maps, again using impedance as spatial-guide and K-Phi laws statistically derived for each rock type.

Stratigraphic sequential analysis divides Mulichinco reservoir in 11 subunits. For each of these subunits a 2D map was built and extrapolated to build the 3D geological model of Aguada Pichana Norte area.

This 3D model was then used to calculate isonet gas for each subunit and, by addition, for the Upper; Middle and Lower Mulichinco.

3.2 Reservoir behavior

An essential step in the development of Aguada Pichana Norte field is the search for "sweet spots" i.e. low impedance anomalies leading to good productivity wells. These "sweet spots" would correspond to good porosity and permeability areas. However, one of the main concerns is that the relation between porosity and permeability depends strongly on rock type (cf. Geological Model Construction Figure 7).

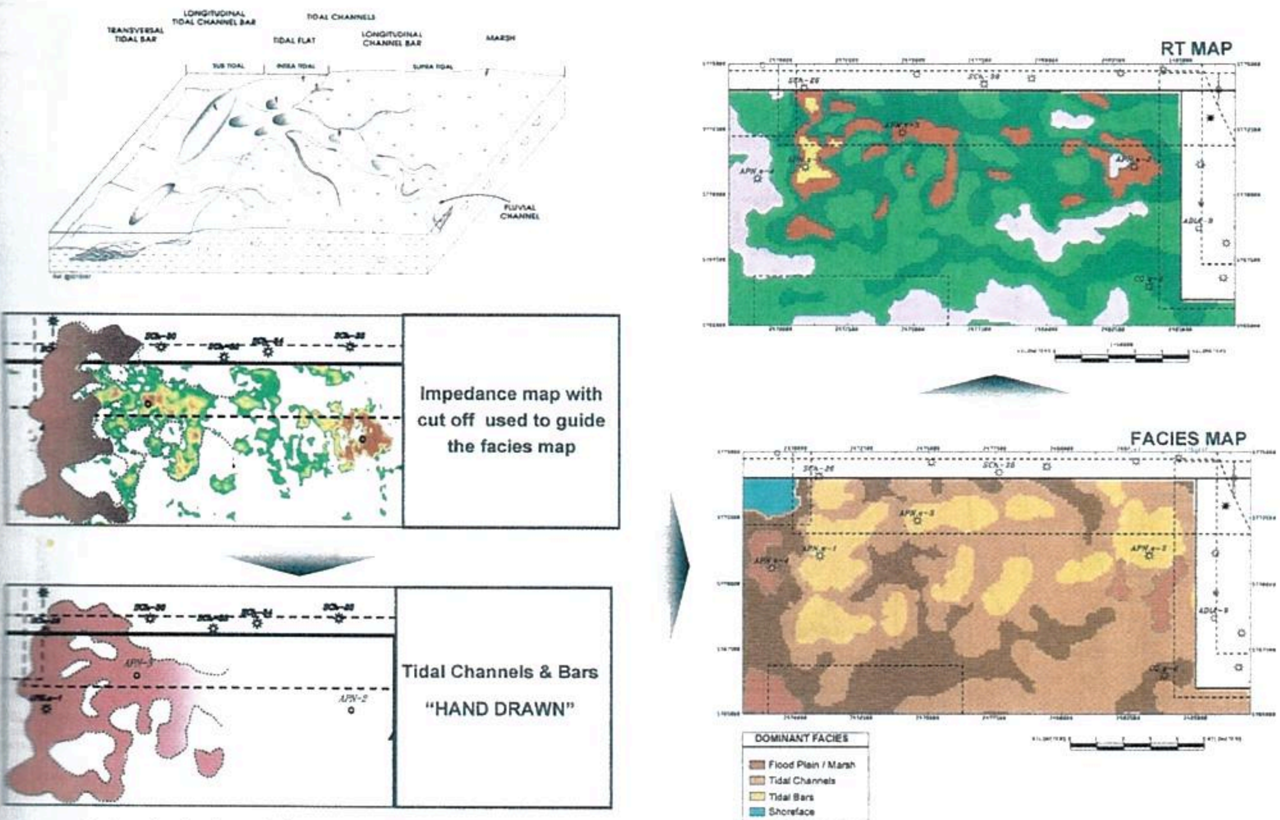


Figure 7. Geological model construction scheme.

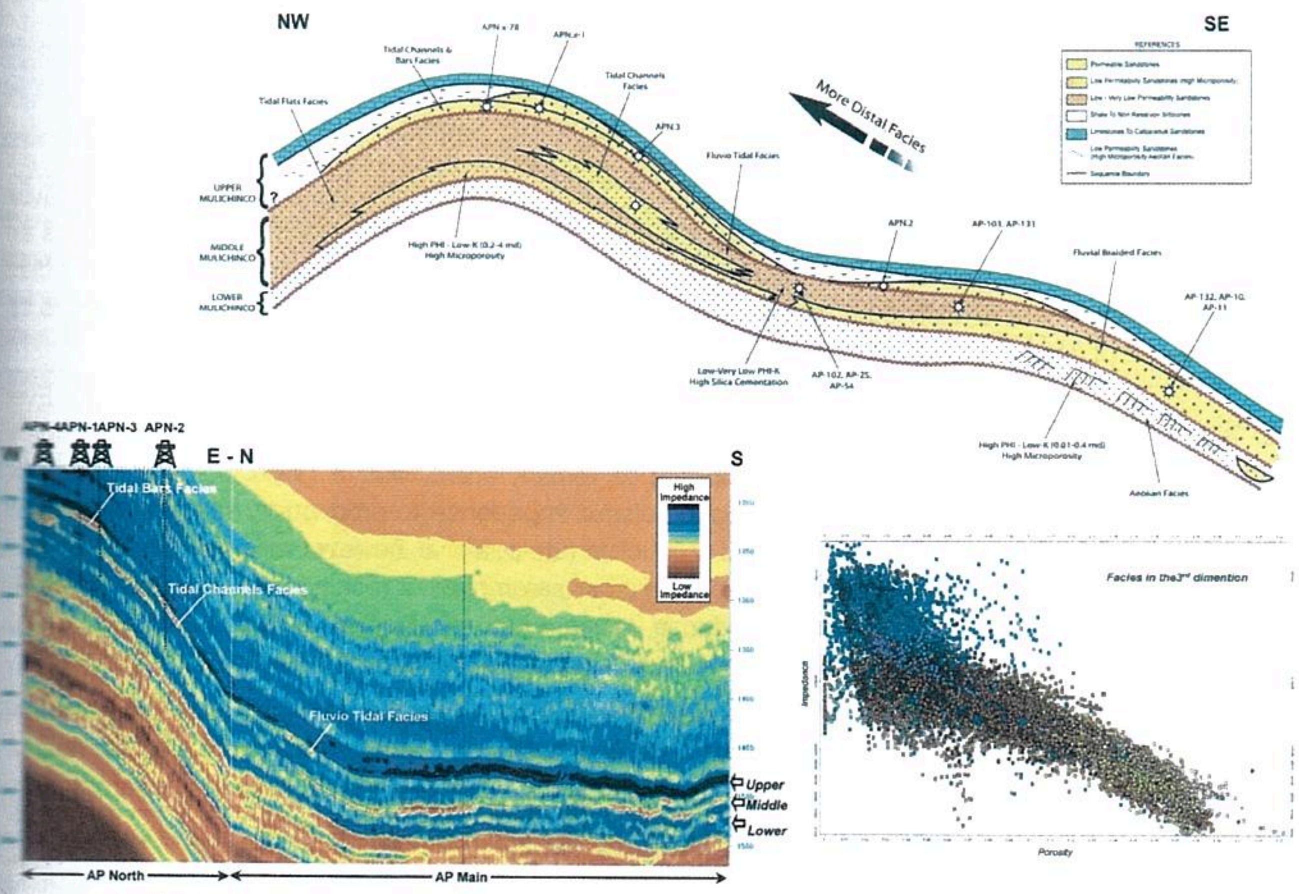
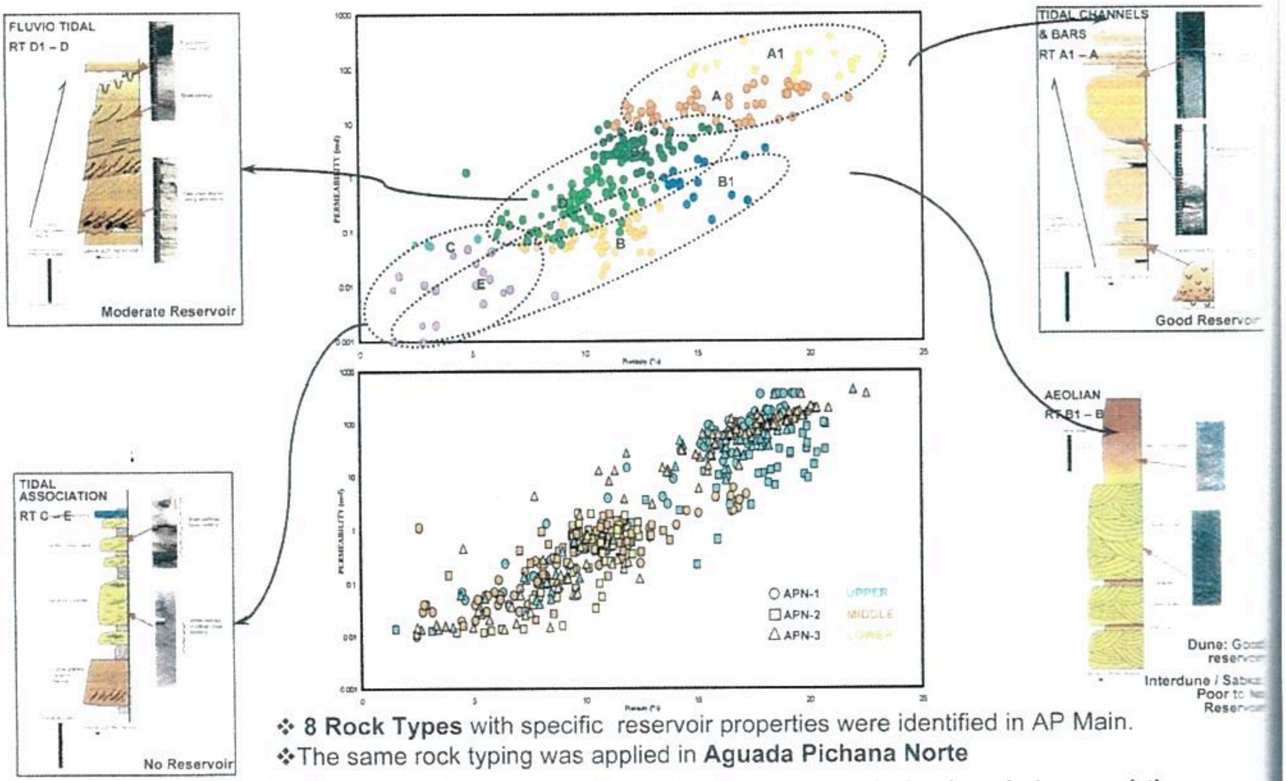


Figure 8. Left:Seismic inversion interpretation. Shown features in Upper Mulichinco are interpreted as tidal channels, tidal bars and fluvial to tidal channels. Right: In AP main wells, porosity increases as acoustic impedance decreases.



❖ **8 Rock Types** with specific reservoir properties were identified in AP Main.

❖The same rock typing was applied in **Aguada Pichana Norte**

Figure 9. In AP Norte 8 rock types with specific reservoir properties were identified and related to a facies association.

The acoustic impedance inversion of APN-3D survey identified stronger low impedance anomalies in the Upper Mulichinco (Figure 11) and Middle Mulichinco.

The relation between acoustic impedance on one side and porosity on the other side was established for available wells in the area (see Figure 10). Cross-plots of acoustic impedance vs. porosity show an effective porosity increase when impedance decreases. The best sweet spots are found in the Upper Mulichinco and Middle Mulichinco Highstand. Low impedance values in these levels are related to high porosity anomalies present in tidal channels and bars. Drilled wells in these units are in general good producers. The Lowstand of Middle Mulichinco (mainly corresponding to eolian facies) also shows a linear relation impedance/porosity. However, permeability is an important issue due to the presence of (intercrystal) microporosity strongly affecting effective porosity.

As mentioned before, low impedance values and sweet spots relation is not straightforward. Even though in neighboring wells fields seismic impedance anomalies serve as a good qualitative guide to estimate the effective porosity, it is important to remark again, that a good porosity to seismic impedance relation does not imply any good seismic impedance to productivity relation. The "sweet spots" tend to indicate areas with high well production rate potential, however reservoir properties such as micro-porosity may have a negative impact in other parameters of rock typing such as permeability or water saturation. The relation low impedance values = high productivity is only statistically verified. Therefore a seismic anomaly is not sufficient as an indicator of sweet spot in terms of productivity.

In APN case, the presence of gas accumulation was proven at the moment of spudding APN well (gas was proved in all the east flank of Chihuidos Anticline).There was neither risk of top seal nor of Mulichinco reservoir presence. The main concerns were related to reservoir characteristics (existence of good permeabilities) and fluid properties (CO_2 content) in the area.

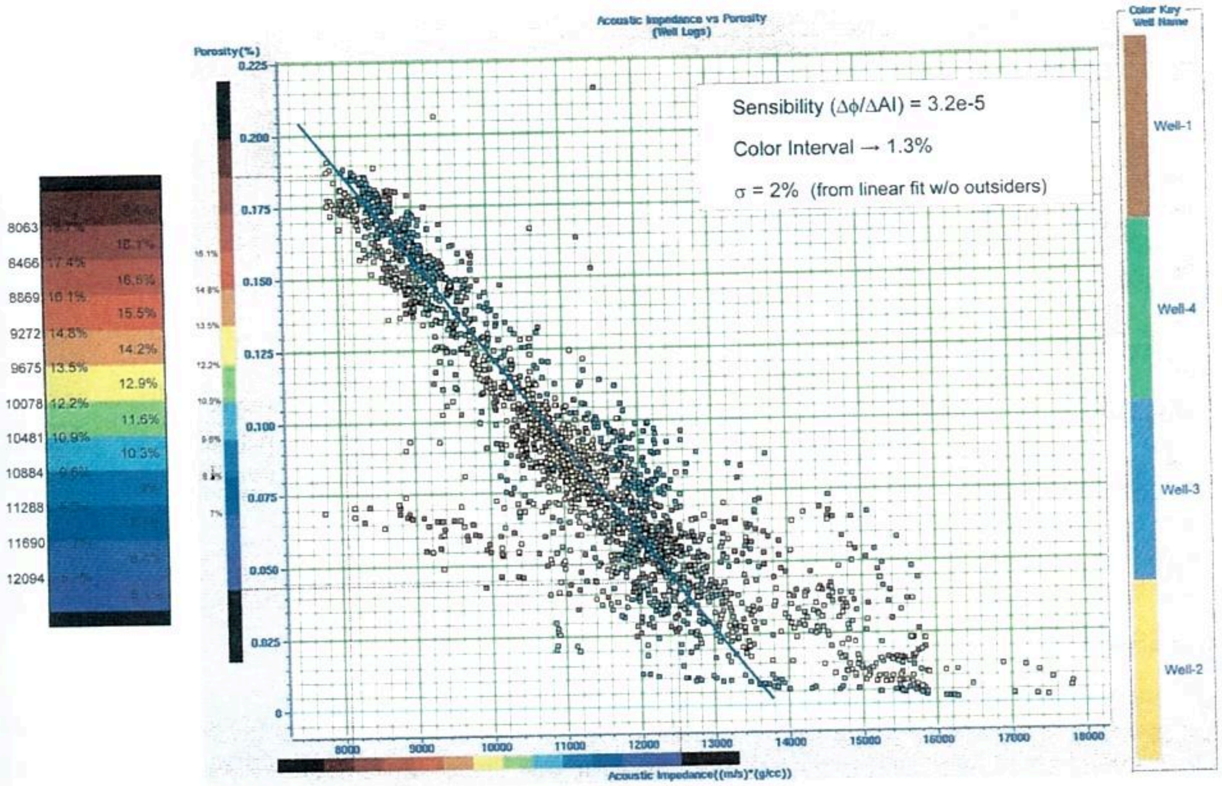


Figure 10. Porosity Impedance Relation.

Aguada Pichana Norte prospect was thus defined in 2002 supported by acoustic impedance indications. Several criteria were then considered (number of objectives assessed in the Mulichinco, relation between impedance anomaly, total gas connected, topographic constraints) to finally choose a position for the first exploratory well (Figures 11 and 12). According to the geological model, the APN.x-1 main objectives (Upper Mulichinco) were expected to be developed in a near shore depositional environment that consists of stacked tidal bars separated by mud/sand tidal flats. Neighbor wells data show that this facies is in general associated with rock types of good reservoir properties in terms of porosity/ permeability. The secondary objective, the Lowstand Middle Mulichinco member was expected to belong mainly to aeolian facies. These facies could develop good porosity but related in part with intercrystalline microporosity. The main uncertainty related with Lower Mulichinco sandstones is the reservoir quality owing to the presence of iron-bearing chlorite: in neighboring wells the entire interval is dominated by authigenic chlorite which could reduce intergranular pores to non-effective micropores.

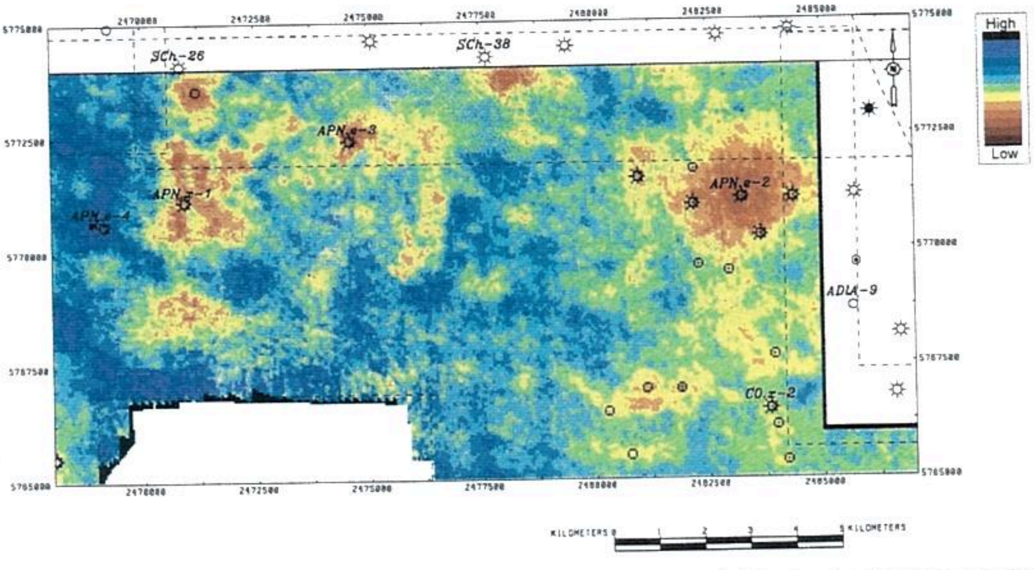


Figure 11. Upper Mulichinco Impedance Minimum: Potential sweet spots were identified.

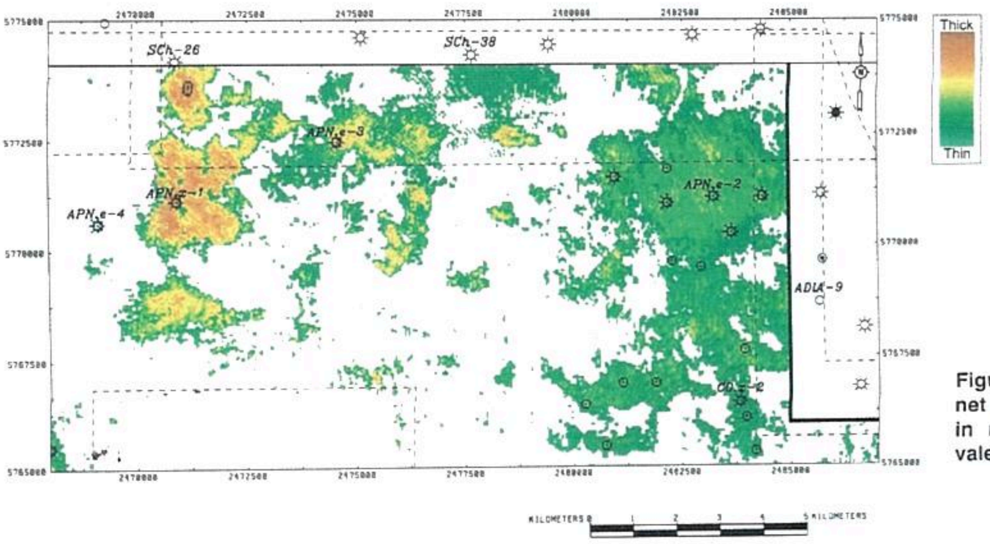


Figure 12. Upper Mulichinc net impedance thickness (tw in ms) with a cut-off equivalent to 12 % porosity.

4. RESULTS

The well APN.x-1 was drilled in December 2004. It was meant to acknowledge the extension c facies with good reservoir characteristics in the area and, in effect, AP Norte prospect was successfu recognized. APN.x-1 proved excellent productivity in the Upper Mulichinco sandstones with averag porosities of 13%, permeabilities around 100 mD and gas rates of 0.5 Mm³/d (with 4.5% CO_2) witho hydraulic fracturing. Upper Mulichinco potential sweet spot was therefore confirmed. The reservoir ha 18 m of net thickness which is approximately the vertical seismic resolution thickness. The two uni composing the reservoir are not resolved by the inversion (Figure 13). The Lowstand Middle Mulichinc was also tested with good porosities however permeabilities were very poor leading to low productio and high CO_2 rates. This was an important benchmark stressing the limitations of acoustic impedan in sweet spot detection (concerning the permeability behavior).

After the good results of this first well, the 3D geological model was updated through a ne acoustic inversion including APN.x-1 impedance calibration in the initial model. The new inversi confirmed the first one and showed some interesting differences (mainly related to lower impedan values) in Upper and Lower Mulichinco units (Figure 14). Updated impedance and 3D model we used to locate two additional appraisal wells (APN.e-2 and APN.e-3) with Upper Mulichinco (tic channels sands) objective that were drilled in December 2005. The aim of these wells was to provi a better description of the spatial variation of reservoir properties, analyze CO_2 distribution, evalua depletion, if any, through Sierra Chata and Aguada de la Arena fields and help in the estimation reserves. After these wells the inversion was newly updated (Figure 15). The last delineation we APN-e.4 was drilled at the beginning of 2007. Impedance prognosis error at this stage was very (Figure 16).

Nowadays 9 wells (APN.x-1, APN.e-2, APN.e-3, APN.e-4, APN-5, APN-6, APN-7, APN-8 and AP 9) are located in APNorte area. Some additional wells with the same objective are located in neighboring area (the wells RDV.x-1, RDV.a-2, AP.a-78 drilled by YPF) constituting an important data for the geophysical-geological model calibration.

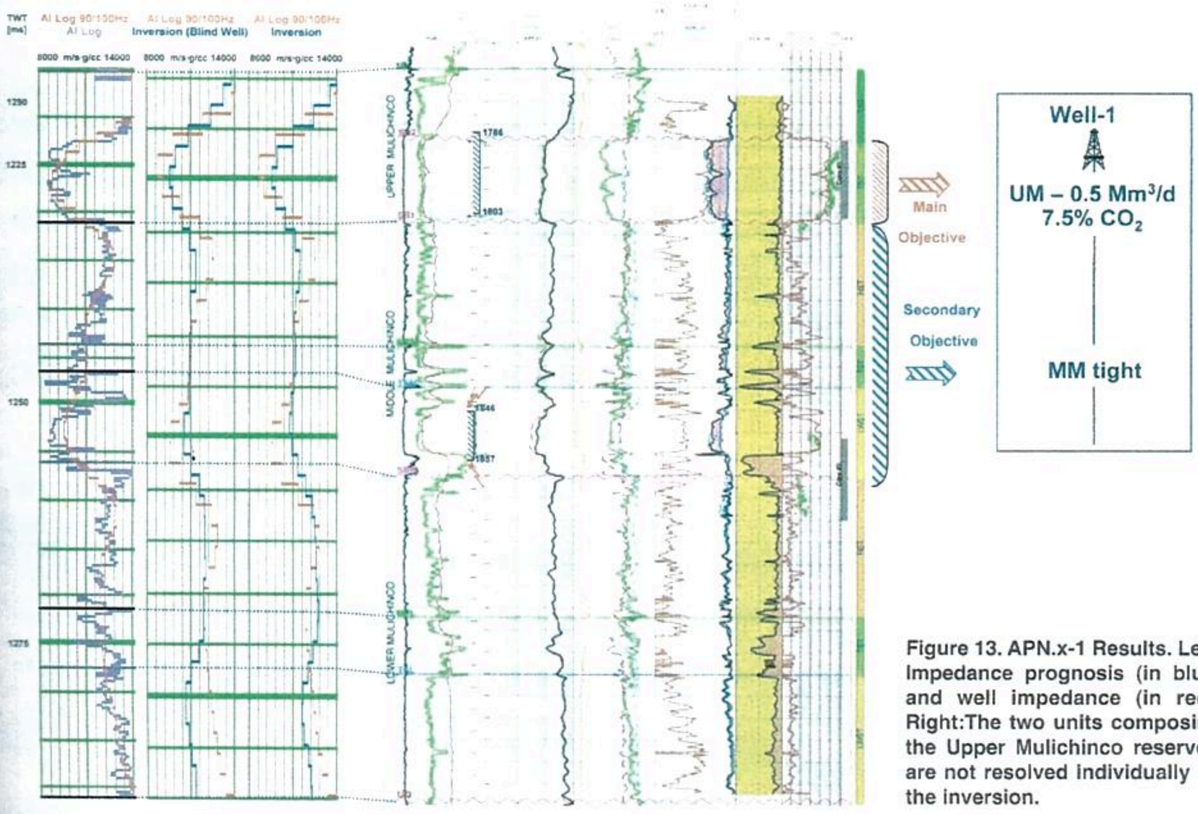


Figure 13. APN.x-1 Results. Left: Impedance prognosis (in blue) and well impedance (in red). Right:The two units composing the Upper Mulichinco reservoir are not resolved individually by the inversion.

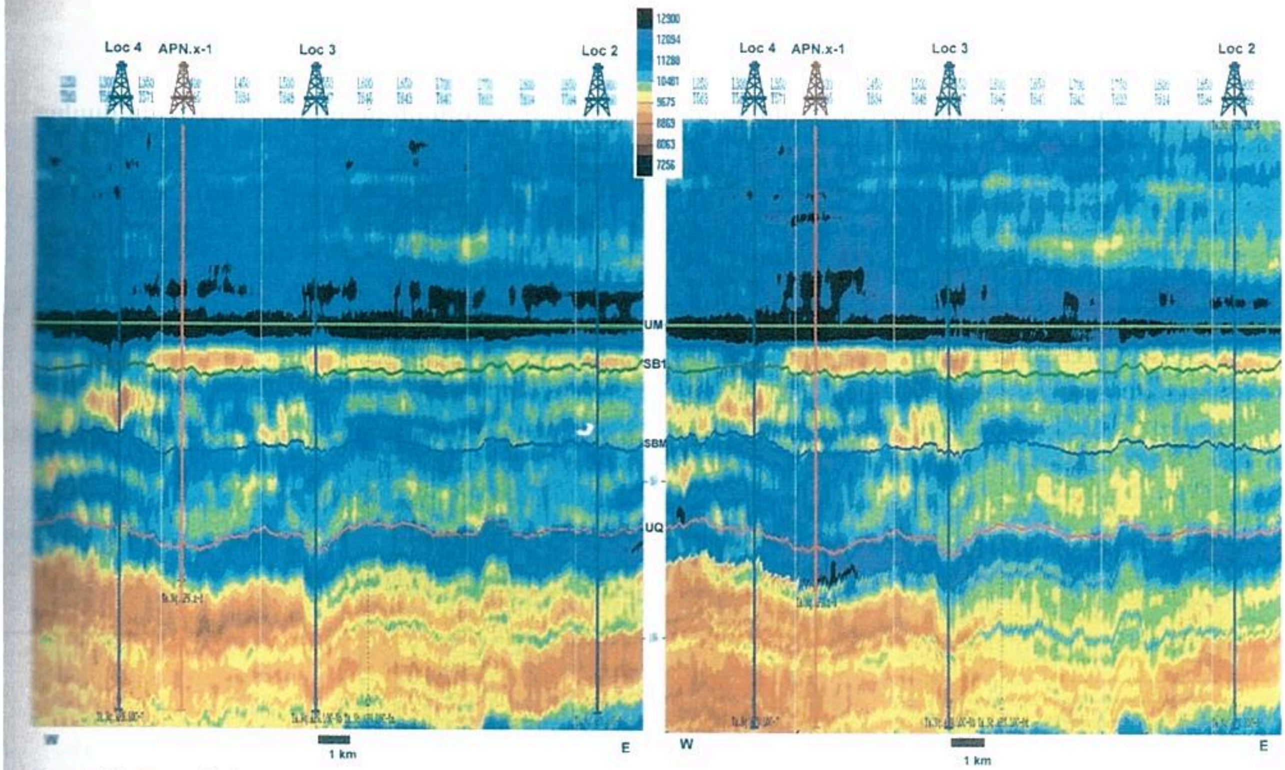


Figure 14. Acoustic Impedance seismic section before (left) and after (right) drilling of APN.x-1.

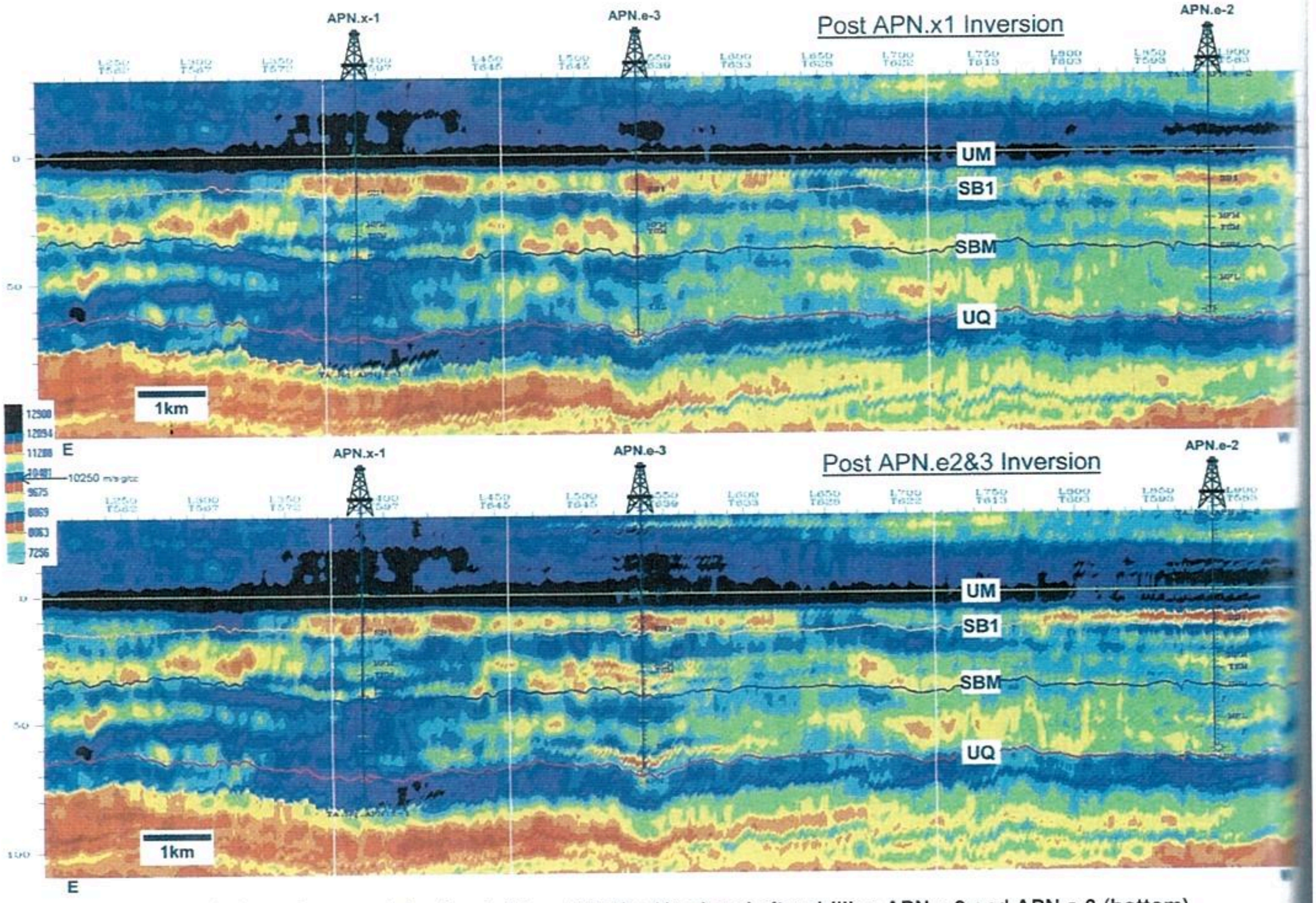


Figure 15. Seismic Impedance update after drilling of APN.x-1(top) and after drilling APN.e-2 and APN.e-3 (bottom).

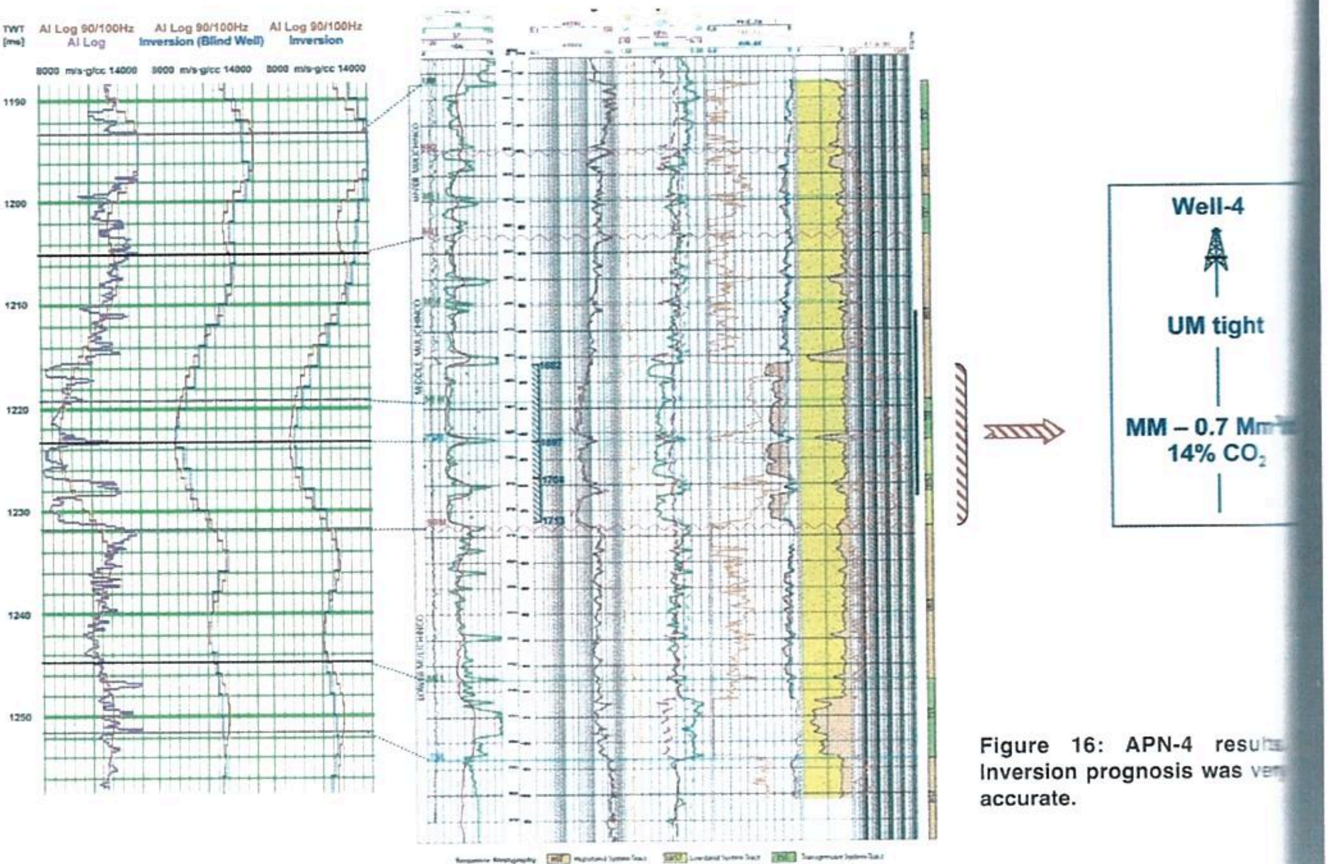


Figure 16: APN-4 resu
Inversion prognosis was ve
accurate.

CONCLUSIONS

Acoustic Impedance Inversion is a fundamental tool in AP exploration and production cycle. Exploration prospects and development wells locations are defined by the acoustic impedance inversion (because of its relationship with the formation porosity) and the geological model (which tries to predict diagenetical events).

In-house inversion allows continuous calibration, improvement and parameter optimization during the exploration and production cycle. In this sense, the interpreter geophysicist is involved in the acquisition and processing stages and he is also in charge of the acoustic inversion.

A detailed knowledge of the inversion quality at each sequence and sector of the area of interest has a direct impact on development wells locations and consequently on drilling campaign results. Inversion accuracy is strongly affected by amplitude "preservation" problems and/or amplitude issues related to surface conditions, acquisition source (vibro or dynamite) and variations in energy dissipation during wavefield propagation. In the case of AP seismic data, strong efforts were done to improve the effective bandwidth. Mulichinco reservoir development strongly depends on the 60/80 Hz high frequency band information.

Acoustic impedance driven exploration and development of APN were successful. It is nevertheless important to remind that the method validity is statististical thus implying limitations in its use as sweet spot detector in the case that the assumed relationship between effective porosity and permeability, breaks down.

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