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Development of deep thin reservoirs through meandering morphologies imaged in seismic data. – A case study in San Jorge Basin, Argentina

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Abstract

This study was focused in the North of Los Perales Field, in San Jorge Basin, Argentina where very good results were obtained identifying extremely heterogeneous fluvial channel reservoirs by using strata slice seismic amplitude data combined with Spectral Decomposition. This last method is a relatively new technology and proved to be useful for mapping thin layers below the seismic resolution. The fluvial channels are well mapped in Castillo Formation, a multilayer reservoir characterised by sandstone bodies deposited by fluvial river systems with high pyroclastic content.

Although more than 3000 wells have been drilled in the field, few ones have reached the deep reservoirs in Castillo Formation.

We showed how the wells LP-2339 and LP-2355 have been drilled in order to evaluate the morphologies visualised with seismic data and how their productions are highly up the average well production in the field.

Seismic cubes at different frequencies were generated, and by blending some of them, it was possible to visualise different channels facies. The thin layers thickness of the reservoir in time produce tuning effect enhancing the frequency data allowing to understand the meandering morphologies representing fluvial channels, its possible depositional environment, and the paleocurrent in the main productive Formations. Because of the sand layer thickness and petrophysical properties of the reservoir, it was not possible to determine the reservoir fluid content by using seismic data alone, but now we know that all of the meandering morphologies showed in strata slices correlates perfectly well with high acoustic impedance sandstones.

These results, give us an extremely useful tool to improve well location in San Jorge Basin, especially in the western zone where the contrasts of impedance between sandstone and tuff are important.

Finally based on this study, new reserves will be incorporated in the area and a new development front is now open in this mature field.

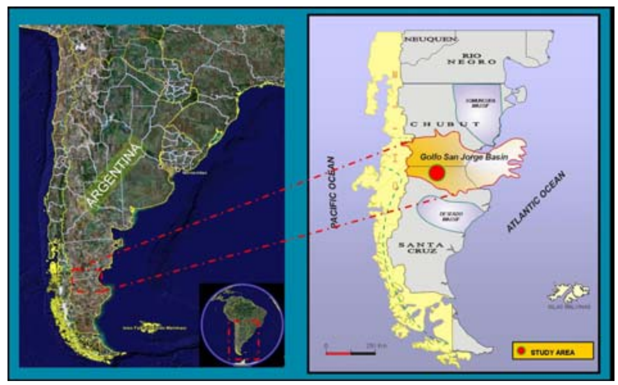

Figure . 1- Location of Los Perales Field in San Jorge Basin.

Introduction

Los Perales is a mature and prolific hydrocarbon field in the western part of San Jorge Basin. The case study was placed on La Itala, in the North of Los Perales Field (Figure 1). More than 3000 wells have been drilled in the entire field on a 300 m spacing. At present, about 1800 wells are producing oil at an average flow rate of 3 m^3 and each year 40 to 100 development wells are being drilled. The producing reservoirs are fluvial deposits of the Cretaceous Chubut Group. The sandstone bodies have great spatial variability and are distributed along a 1500 meters sediment column in Bajo Barreal Formation and Castillo Formation. For years, well locations were proposed based on structure defined with 2-D or 3-D seismic data and sandstone trends predicted from well correlation. The correlation of individual sandstones bodies is greatly dependent on assumptions regarding their geometry and spatial distribution, and this is based on uncertain interpretation. Reservoirs connectivity is defined using well by well production history and pressure measurements. The high pyroclastic content in Castillo Formation deteriorates reservoirs conditions, porosity and permeability, and this difficult fluid prognosis.

In this case study we document how, complex and heterogeneous fluvial sandstones reservoirs as thin as 5 m and with meandering morphology can be imaged with 3-D seismic data and how this information was key to drilling two successful wells. We performed this study in an area where the producing interval is Bajo Barreal Formation. The reservoirs were visualized at about 1550 m depth, in Castillo Formation and had not been penetrated by any of the large number of production wells in the area. The description of selected outcrops of the Chubut Group in San Bernardo Range and vicinity (Bridge et al, 2000) revealed most of the rivers as being single-channeled and sinuous with the presence of braided rivers also. Individual channel width was on the order of tens of meters (mainly 35 to 65m) and the maximum channel depth was on order of 2 to 6 meters. Paleocurrents flowed eastward- southeastward. Geometry and orientation of the channels mapped with seismic are similar to those interpreted from surface data but seismic imaged channels seem to be wider than average outcrop data.

Regional Geological Model

The San Jorge Basin has an extensional origin and is Intraplate confined with mostly continental deposits. Its evolution is characterized by two tectosedimentary phases: the Neocomian cycle where lacustrine and marine deposits filled half-graben structures formed by rifting from the Triassic to the Early Cretaceous, and the Chubutian cycle existed for the rest of Cretaceous when the basin was on sag phase filled with continental deposits (Feruglio, 1949; Fitgerald et al 1990, Hechem et al, 1990). The source rocks of the study area are the black shales of D-129 Formation deposited in a large lake during the late Barremian and Aptian age. Expulsion and migration of hydrocarbon could have started 100 Ma ago.

Most of the hydrocarbon produced on San Jorge Basin comes from fluvial sandstones of the lower member of Bajo Barreal Formation. Sandstones bodies have been deposited by ephemeral rivers with sudden and episodic events and conditioned by volcanic activity (Bridge et al, 2000). Sandstones sheets, wedge and lenses were identified on outcrops and represent the deposits of overbank sheet floods, levees, and crevasse splays respectively. Channel-form sandstones bodies represent channel bars and fills within channel belts.

The normal faults system formed by rifting, has strike orientation NW-SE where roll over structures are the dominant traps. Extensional style was superimposed by a compressive system whose orientation is NNE-SSW. Compression and uplift was intensive in Los Perales field, and was initiated in the Tertiary, associated with regional uplift of the Andes Range on the west (Homovc et al, 1995; Peroni et al, 1995). Tectonic inversion also provided favorable structural traps and path for hydrocarbon migration (Hechem, 1994; Homovc et al, 1995).

Most of the productive reservoirs on the basin are on the Chubut Group which comprises D-129, Castillo and Bajo Barreal Formation. The transition zone between Castillo and Bajo Barreal Formation is informally called *"Seccion Tobacea"* and the authors included this section on the Castillo Formation. The Chubut Group thickness varies from 500 to 2000 m (Sciutto, 1981; Peroni et al, 1995). Lateral variation of thickness is gradual, increasing in the downthrown sides of regional normal faults. Seismic reflections are subparallel and clinoforms are absent. The composition of the strata is sandstones and mudstones with abundant volcaniclastic material provided from a western source. The Castillo Formation is dominated by volcaniclastic material, particularly green tuff (Sciutto, 1981). The sandstone bodies in these formations are up to 15 m thick with most of them measuring from 2 to 6 m thick. Estimates of the width of sandstones bodies vary from several hundred meters to kilometers (Fitzgerald et al, 1990; Jalfin et al, 1996).

Imaging thin reservoir on 3-D seismic

The study was focused on deep thin reservoirs with very good hydrocarbon potential which were mostly undeveloped due to uncertainties to predict their areal distribution. The presence of good reservoir in Castillo Formation has been noticed in many exploration and development wells on the field. However, lack of understanding of reservoir spatial distribution and budget limitations to drill deeper wells, constrained oil production to Bajo Barreal Formation.

The possibility to visualize thin-bed reservoirs below seismic resolution means that at least three conditions have to be present:

1- Impedance contrast between reservoir rock and adjacent rock and reservoir thickness below seismic resolution.
2- Proper seismic processing (especially amplitude processing)
3- Reliable regional and continuous horizon interpretation, especially structural interpretation in case of complex structures.

Most of the sandstone layers on the field have higher acoustic impedance than shales and tuff around them and is on Castillo Formation where the ancient channels are easily imaged on seismic slices. Seismic data quality is a key factor to recover information from subsurface. Seismic frequency is not as important as is thought on imaging thin-bed. Even in case of acquiring a high resolution seismic survey (i.e. 150 Hz of maximum frequency), and assuming velocities for sandstones of 3000 m/s, the half wavelength is 10 meters, almost double than average thickness layers. Meandering morphologies are imaged on seismic because constructive wave interference is produced as a seismic response of thin layers. As a result, the geological features representing deposits of fluvial channels are enhanced in amplitude display and can be followed on horizon or stratal slices.

We started with the methodology selecting a continuous and regional seismic horizon near the stratigraphic section to be analyzed. The horizon selected was called Intracastillo; was a positive pick near the top of Castillo Formation and represents a regional shaly zone (Figure 2).

The assumption when mapping a continuous seismic reflection event is that we define a geologic surface that corresponds to a fixed, constant depositional time. In other words, seismic reflections follow chronostratigrafic depositional surfaces (Vail and Mitchum, 1977).

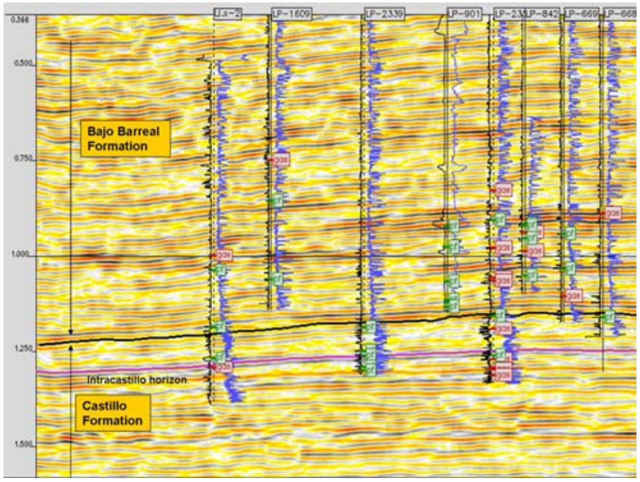

Figure. 2 –Reference horizon Intracastillo was displayed in red color. SP and resistivity logs were displayed along the boreholes on the left and right respectively.

The entire 3-D data volume was flattened in relation to the reference horizon. Seismic reflections of Cretaceous deposits are parallel on most of the volume data. So it was assumed that any horizontal time slice in the flattened seismic cube also followed an ancient depositional surface. Stratal slices were generated every 4 milliseconds in the vicinity of the reference horizon Intracastillo. A single canalized feature is usually visualized for several milliseconds, depending on the seismic frequency. The drilled sandstone channels were imaged approximately during a 20 milliseconds interval starting to be visualized 8 ms above Intracastillo horizon (Figure 3). As we moved down across the peak-trough anomaly generated as a seismic response of the thin bed, the imaged features changed from positive amplitude to negative amplitude (for high acoustic impedance sandstones). The ancient rivers visible on slices were plotted in a grey scale, which corresponds to variable amplitude and reflects varying lithology characteristics. We could not translate grey scale in terms of lithology, but we were able to represent contrasts between channel, overbank and other lithologies.

The mapped meandering system flowed southeastwards and could be followed on the seismic data for at least 15 kilometers. The maximum single channel width was 270 m and the average measured width was approximately 150 m. The total sinuosity of the channel segment was medium to high with a computed value of 1,6. A regional model was performed to reconstruct the depositional environment (Figure 4). The paleodrainage pattern was longitudinal to regional normal faults, and fan deposits were found on the faults slopes, perpendicular to the river system.

The analysis of the seismic data processing was not in the scope of this paper. However the authors want to remark the great differences on quality of the visualized channels when post-stack seismic data was used compared with pre-stack seismic data. The amplitude slices from post-stack data had clearly better image definition with a broader contrast on amplitudes than pre-stack data. Similar analysis was done with a different 3-D seismic survey acquired in the basin arriving to the same conclusion. It is important to clarify that reference horizons used to flatten the post-stack and pre-stack data were at the same stratigraphic level and interpreted independently in each seismic cube.

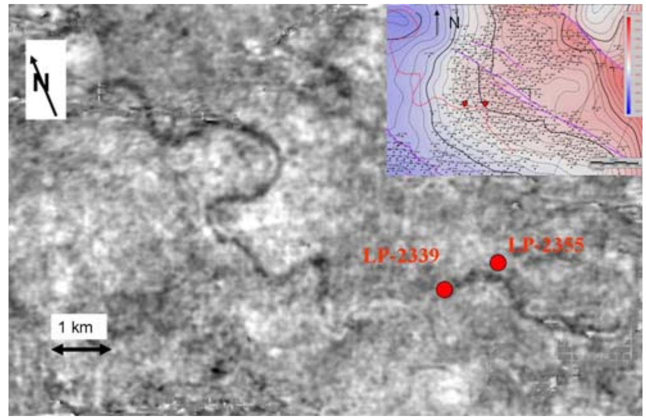

Figure. 3- Horizon slice showing the meandering ancient river and the wells LP-2339 and LP-2355 drilled on this reservoir. Above in the right the structural map in time of Castillo Formation top with all the wells drilled in the area and the location of the mapped channel.

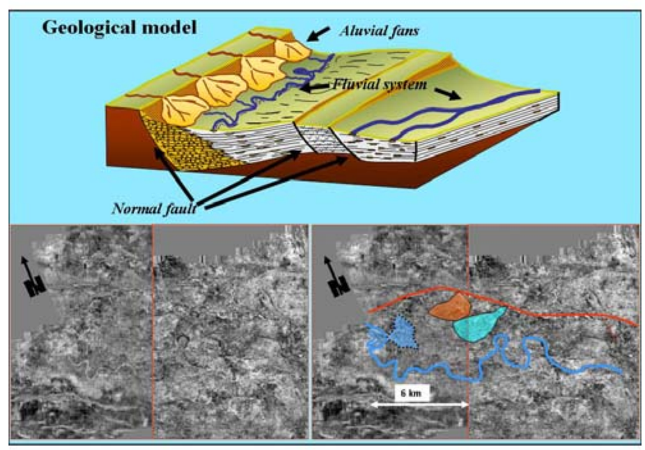

Figure. 4- Regional model showing the major normal fault (in red) and the paleodrainage pattern longitudinal to the fault. Aluvial fan deposits were detected on the slopes of the faults (Modified from Pulido, L., 2004).

Use of spectral decomposition and attributes analysis

Spectral decomposition and thin-bed tuning phenomena can be illustrated by a single wedge model. When the thickness of the layer in time is such that top and bottom reflections are resolved separately, seismic record images the characteristics of each boundary separately (the top of the wedge is marked by a positive reflection coefficient and the bottom by a negative reflection coefficient in the case of high acoustic impedance sandstones). As the wedge thins, reflected waves experiment constructive interference first, and then destructive interference. This is called tuning effect and generates amplitude variations indicating the limit of the vertical resolution. Seismic resolution depends on wavelength that is related with dominant frequency in the seismic spectrum and seismic wave velocities.

The wedge model is an approach to a very simple two-reflector reflectivity model. Increasing the complexity of the reflectivity model will in turn complicate the interference pattern.

Spectral decomposition technique transform seismic data into the frequency domain via discrete Fourier Transform, thus a reflection from a thin bed has a characteristic expression in the frequency domain that is indicative of the temporal bed thickness (Partyka et al, 1999).

The first step we carried out was to determine which frequencies improved the fluvial features detection. The dominant spectrum frequency of the data at the reservoir depth was 35Hz, and we found that some parts of the fluvial system were better imaged at 30 Hz and some others at 50 Hz.

Seismic cubes with a unique frequency content (isofrequency cubes) were calculated at those frequencies and, after that, they were flattened in order to remove the structural effect allowing the mapping of meandering morphologies. Blending horizon slices at different frequencies together with amplitude slices permitted to define gentle details about geometry and spatial distribution of channels (Figure 5).

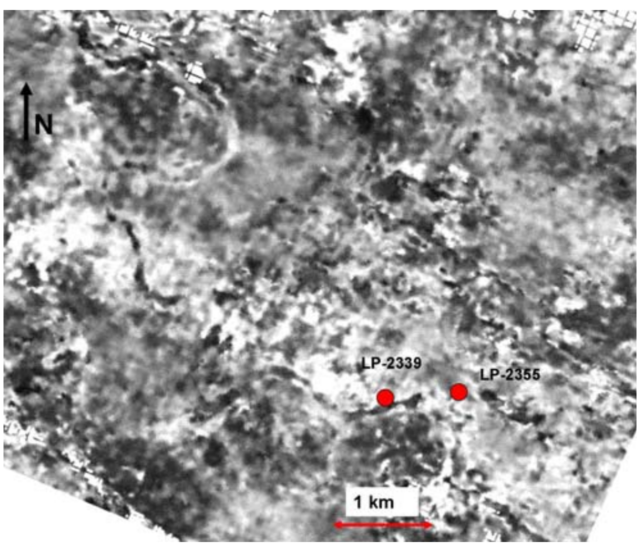

Figure. 5 – Slice showing blending data of isofrequency cubes at 30 Hz, 50 Hz, and amplitude slices data.

Seismic attributes were unable to improve data information provided by amplitude analysis. Half energy and Instantaneous frequency were computed in a narrow interval around the seismic event representing the channel. Probably the most significant result obtained with attributes was the good matching between sandstone packages represented by the meandering morphology with the high frequencies exhibited on instantaneous frequency data.

Methodology application on well proposal

The well LP-2339 was drilled on a smooth positive structure faulted transversely by normal faults. Sandstones packages trends on Bajo Barreal were quite accurately known based on well log correlation between tens of wells drilled on the zone. However, few wells penetrated Castillo Formation with no oil production on this block. The well LP-2339 had a final depth of 1630 m, and penetrated the border of the meandering features detected on slices analysis. A total of ten layers of sandstones were swab tested on Castillo Formation, five of them with oil production (Figure 6) and original reservoir pressures. Although the well had good potential oil bearing sandstones on Bajo Barreal Formation, none of them were tested in order to estimate the final cumulative production from Castillo Formation. Four layers were fracced and the initial oil flow rate was 30 m^3 per day. After twelve months of production, the oil flow rate was 10 m^3 per day and the gas flow rate 6500 m^3 (gas dissolved) and the final cumulative production of oil is estimated to be 13200 m^3. Those values exceed considerably the average daily well production on the field (3 m^3/day) besides exceed the total accumulation of oil necessary to be a profitable well, defined in a value of 7180 m^3 of oil in 72 months.

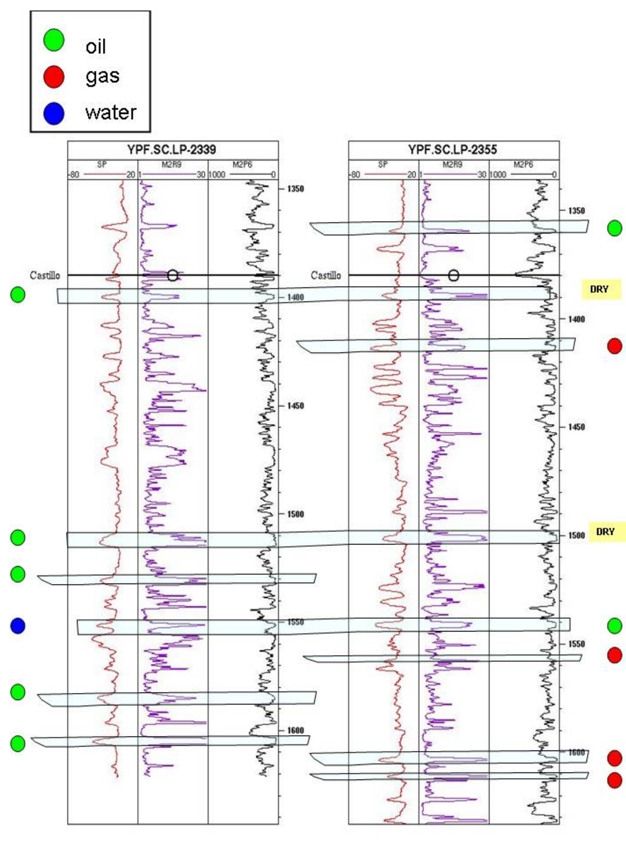

Figure. 6 – Well log correlation. From left to right the log curves are, SP, resistivity and conductivity. The layer identified as the channel in seismic was at 1515 m in LP-2339 well and the swab test in this layer was dry in LP-2355 and oil in LP-2339 well

The LP-2355 well was drilled consecutively to LP-2339, taking into account the success of the latter. The final well location was modified with respect to the original one due to location restrictions on surface facilities. It was drilled in a margin of the mapped channel and in a higher structural position than LP-2339. The final depth was 1654 m and six sandstone layers were swab tested on Castillo Formation, finding five of them holding gas, and one holding oil. The initial flow rate of the oil bearing sand in Castillo was 2500 liters/hour. The initial oil production of the well was 13 m^3, with one oil layer in Castillo and two in Bajo Barreal. The gas layers were not opened to production, and the final cumulative production is estimated to reach 4163 m^3. The amount of sandstone layers in the upper part of Castillo Formation in both wells was remarkably greater than the average well.

Well tie: Depth thin layers versus river channels on time

A calibration tool was needed to define where a specific thin bed reservoir was to be positioned in the 3-D seismic data volume. The absence of VSP data and sonic logs was not a reason to accurately determine which sandstone layers defined on well logs was represented on stratal seismic slices. A wavelet extraction was performed with VSP data recorded in an exploratory well located 1250 meters southwestward into the same block for the interest interval, resulting in a phase rotation of 90 degrees. After that, synthetic sonic logs were generated using resistivity logs and Smith equation finding a satisfactory match with true sonic logs in test wells. The acoustic impedance log was convolved with extracted wavelet to compute the synthetic seismogram (Figure. 7). Special attention was needed to correctly position vertically the thin sandstone layers inside the 3-D seismic data volume. It was clear that not all sandstone layers have a characteristic thin bed response on seismic.

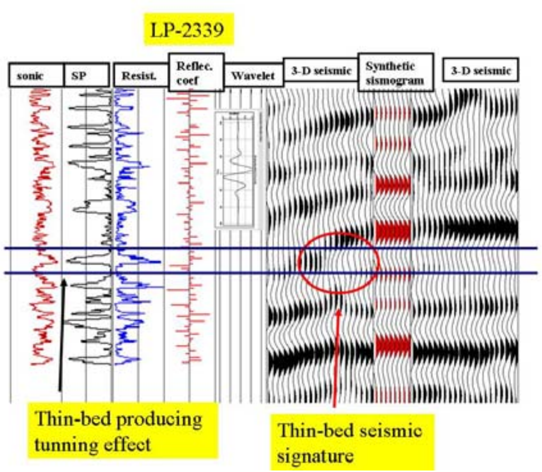

Figure. 7 – Synthetic seismogram generation in LP-2339 well with a 90 degree rotated wavelet. The stratigraphic interval producing seismic anomaly was pointed in the picture.

The interest reservoir mapped on seismic was identified on LP-2339 well to be a fining upward sequence of 15 meters thick with a massive sandstone layer of 8 meters on the base at 1515 meters depth. The same sequence was poorly developed on LP-2355 well and had worse petrophysical conditions, which agreed with the well location near the channel margin. Although it was not possible to predict many of the other narrows reservoirs also penetrated in the upper part of Castillo Formation because of their lack of thin-bed seismic response, we could conclude that wells were drilled in an ancient fluvial channel valley, were ancient rivers have been migrating on the channel belt leaving their deposits in an extensive area around the visualized channel with important deposits in the vertical column.

Conclusions

The use of 3-D seismic amplitude analysis on flatten slices supported by spectral decomposition is the unique tool capable of directly imaging channel sinuosity and splitting, and measuring the width of channel belts on the subsurface. This is also the only method that can be used to predict the spatial distribution of channel-belt thickness and lithofacies.

The spatial distribution of the complex multilayer deep reservoirs detected with 3D seismic allowed optimizing location proposal of two wells which proved the presence of many hydrocarbon bearing sandstones in Castillo Formation, with oil flow rates higher than average. With this study we will be able to incorporate reserves not evaluated to the moment. We will also have the opportunity to continue the block development by drilling infill wells or deepening old wells to reach the Castillo Formation reservoir visualized on seismic data.

The methodology of amplitude slices was successful delineating features below seismic resolution. It helped in improving geological models about spatial distribution of fluvial system, and obtaining information about paleocurrent and geometry of ancient river channels. It was required to posses a reliable method to tie the sandstone body layers detected on well logs with seismic data to understand the stratigraphic distribution of the reservoirs and to optimize future well locations. Spectral decomposition added subtle information about channel geometry not detected solely with amplitude data.

We want to remark that with this analysis was possible to predict deep reservoir location, but we were unable to estimate the petrophysical quality of the reservoirs and the fluid content.

Acknowledgments

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References

1. Bridge, J., Jalfin, G., and Georgieff, S.: "Geometry, Lithofacies, and Spatial Distribution of Cretaceous Fluvial Sandstone Bodies, San Jorge Basin, Argentina: Outcrop Analog for the Hydrocarbon–Bearing Chubut Group" Journal of Sedimentary Research, Vol.70, No. 2, March, 2000, 341-359.

2. Feruglio, E.: "Descripción Geológica de la Patagonia", Dirección General de Yacimientos Petrolíferos Fiscales, Tomo 1, 1949, p.350.

3. Fitzgerald, M., Mitchum, M., Uliana, M., & Biddle, K.: "Evolution of the San Jorge Basin, Argentina", A.A.P.G, Vol.74, No. 6, 1990, 879-920.

4. Hechem, J., Homovc, J.F., & Figari, E.G.,: "Estratigrafía del Chubutiano (Cretácico en la Sierra de San Bernardo, Cuenca del Golfo San Jorge, Chubut, Argentina", Congreso Geológico Argentino, Actas 3, 1990, 173-176.

5. Homovc, J.F., Conforto, G.A., Lafourcade, P.A., & Chelotti, L.A.: "Fold Belt in the San Jorge Basin, Argentina: an Example of Tectonic Inversion", Geological Society of London, Special Publiaction 88, 1995, 235-248.

6. Peroni, G., Hegedus, A., Cerdan., J., Legarreta, L., Uliana, M., & Laffitte, G.: "Hydrocarbon Accumulation in an Inverted Segment of the Andean Foreland: San Bernardo Belt, Central Patagonia", A.A.P.G, memoir 62, 1995, 403-419.

7. Hechem, J.: "Modelo Predictivo de Reservorios en un Sistema Fluvial Efimero del Chubutiano de la Cuenca del Golfo San Jorge", Argentina. Asociación Argentina de Sedimentología, Revista, 1, (1), 1994, 3-14.

8. Sciutto, J.: "Geología del Codo del Río Senguerr, Chubut, Argentina", Septimo Congreso Geológico Argentino, Actas 3, 1981, 203-219.

9. Jalfin, G.A., Droeven, C., & Minnitti, M.: "Reservoir Geometry of the Productive Chubutiano Sequences in the Western Area of the South Flank of the San Jorge Basin", Reservoir Characterization Meeting, Mendoza, 1996, 37-39.

10. Vail, P. R., and Mitchum, R. M., Jr.: "Seismic Stratigraphy and Global Changes of sea Level, Part l-Overview, AAPG, Memoir 26, Seismic stratigraphy-applications to hydrocarbon exploration, 1977, 51-52.

11. Pulido, L.: "Control tectónico de la arquitectura aluvial. La sección tobácea y su potencial petrolífero en el área de la Itala y las mesetas", Unpublished Bulletin, June 2004.

12. Partyka, G, Gridley, J., and Lopez, J.: "Interpretational Applications of Spectral Decomposition in Reservoir Characterization", The Leading Edge, March 1999, 353-360.