

Case History: Hydrocarbon Production Optimization in Cerro Dragon Using Latest Formation Evaluation and Perforating Technologies

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Abstract

Successful hydrocarbon production in the San Jorge basin requires precise understanding of the great variability in reservoir and fluid properties to determine the reservoir production capacity and achieve the optimum wellbore – reservoir connectivity during perforating.

Efforts to increase hydrocarbon production in the Cerro Dragon area of the San Jorge Gulf basin have been fueled by a combination of the latest formation evaluation, such Nuclear Magnetic Resonance (NMR) and perforating technologies associated with the extensive experience acquired during several years of team work between the operator and the service company.

The operator's needs for a method to help optimize well productivity and, at the same time, be cost effective without compromising the results of the operation required an improvement over traditional tubing-conveyed perforation (TCP). A propellant-assisted perforating (PAP) method that could optimize well productivity while maintaining stringent health safety and environmental standards was proposed. The PAP method uses an oxidizer that creates carbon dioxide gas at extremely high peak pressures in the millisecond time regime to overcome in-situ stress and creates perforation breakdown and mild fracturing near the wellbore. Standard perforating components and procedures are used, which provides the same safety features as when conventional TCP operations are used.

This paper focuses on different applications for the PAP method. It also describes the benefits of its use in the San Jorge basin, including enhancing connectivity beyond a damaged zone for better production and near the water contact, where hydraulic fracturing is not feasible, as well as reducing the hydraulic horsepower required for perforation breakdown to obtain production from marginal wells and pre-frac stimulation.

Introduction

Historically, formation evaluation and hydrocarbon detection in the San Jorge Gulf basin through conventional logs has experienced major difficulties as a result of great variability in fluid properties, complex lithology throughout the stratigraphic column, and variable formation water salinity. Consequently, the detection and prediction of hydrocarbon productive zones in the San Jorge basin have demonstrated major inconsistencies and anomalous results. These inconsistent and anomalous results occur primarily because of the lack of ability to distinguish between different types of hydrocarbons.

Initially, the use of Nuclear Magnetic Resonance (NMR) technology in the San Jorge Gulf basin was focused on obtaining petrophysical parameters for predicting reservoir production capacity (e.g., porosity, movable and irreducible fluid volumes, and permeability) with marginal results at its early stages. Currently, the latest advancements of this technology has enabled the detection of different hydrocarbon types by using special acquisition parameters of a multi-frequency NMR tool with advanced processing techniques (Acuña et al., 2003; Stinco et al., 2004). The hydrocarbon type in these reservoirs is virtually invisible when conventional resistivity, porosity, and standard NMR methods are used.

The first stage, the hydrocarbon detection and typification, has been successfully completed. The second stage and challenge is the production of the hydrocarbon contained in different reservoir quality types. To reach this goal, the service company suggested the use of an improvement over traditional tubing-conveyed perforation (TCP).

The system consists of a propellant-assisted perforating (PAP) method that optimizes well productivity while maintaining stringent health safety and environmental standards. The use of standard perforating components and procedures provides the same safety features as when conventional TCP operations are

provided and used.

In the last few years, Cerro Dragon oilfield, operated by Pan American Energy, has increased production with respect to other fields in the San Jorge Gulf basin. Key components of this success have been the use of state-of-the-art technologies and continuous improvement processes as part of the process of improving evaluation and understanding of the Cerro Dragon zone reservoir.

This paper focuses on how the improved formation evaluation logging program and its different applications have helped to identify the right place for the use of the PAP method. It also describes the benefits of its use in the San Jorge basin, such as enhancing connectivity beyond a damaged zone for better production and near the water contact, where hydraulic fracturing is not feasible, as well as reducing the horsepower required for perforation breakdown to obtain production from marginal wells and pre-frac stimulation.

Geographic and Geological Description

Cerro Dragon oilfield is located 85 km west of Comodoro Rivadavia (Fig. 1), on the west side of the San Jorge Gulf basin in the Chubut and Santa Cruz Province, Argentina. The area in which Pan American Energy LLC operates consists of approximately 50 different oilfields. Cerro Dragon oilfield has been under development and has operated since 1959.

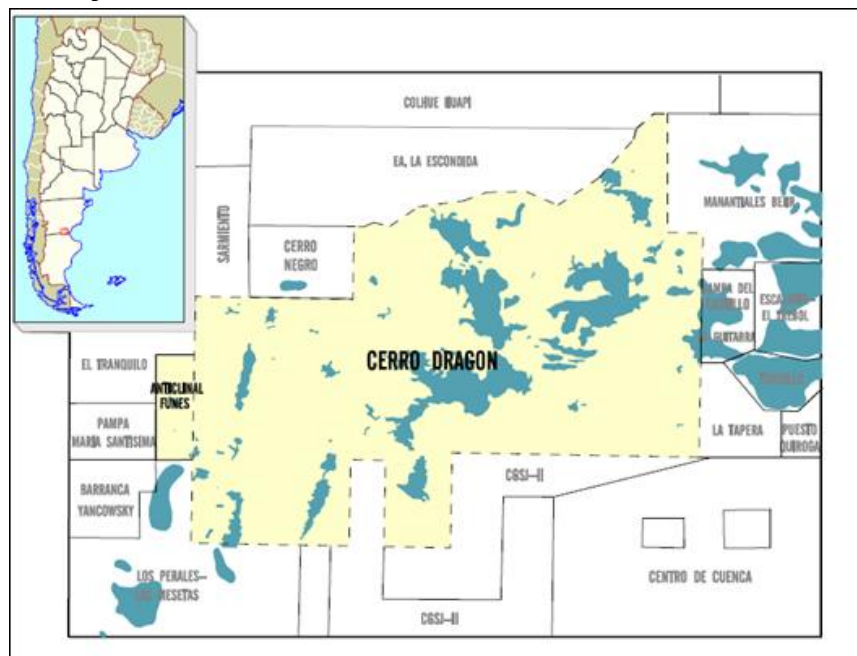


Fig. 1–Location plan.

Reservoir Geology.

Cerro Dragon oilfield consists of an area of 3,480 km². It was formed in a vast basin in the Mesozoic period. Its main filling occurred in the Riftin stages of the late Jurassic period-early Cretaceous; its origin is primarily lacustrine (marshy) and fluvial.

The main productive formations are the Comodoro Rivadavia formation, which consists of shaly sand bodies, and the Mina el Carmen formation, which consists of tuffaceous sands, tuffs, and altered tuffs (**Fig. 2**)

The study zone of the Comodoro Rivadavia formation has an average thickness of 200 m, approximately 90 m of which lie in the pay zone. The thickness of these sands varies from 1 to 8 m. (Acuña et al., 2003, Espina et al., 2009).

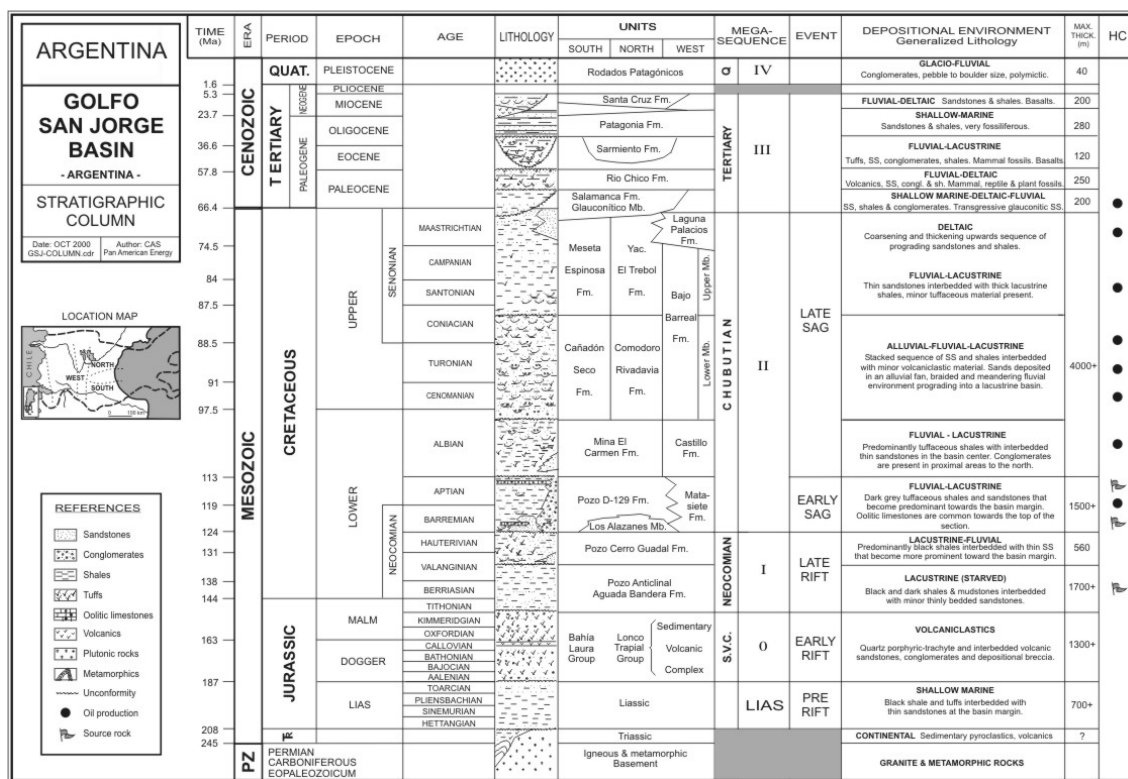


Fig. 2—San Jorge Gulf basin stratigraphic column.

NMR Stand-alone Interpretation Techniques Description

The Enhanced Diffusion Method (EDM) NMR technique uses the contrast in molecular diffusion between water and oil to identify and potentially quantify oil accumulations. The diffusion properties of water, combined with tool parameters (TE, magnetic field gradient) and the temperature of the logging environment, define the slowest possible relaxation time for water to be observed: T2DW. Consequently, any NMR signal observed beyond this value can only be associated with oil. This method provides a simple way to interpret the presence of oil and to differentiate between pay and non-pay zones.

The EDM technique can also be used to quantify residual oil. As with any residual oil determination technique, controlling fluid loss from the mud system to the formation is critical to the overall success of the EDM technique. This method is based on the contrast in molecular diffusion between different fluids. The enhancement of the diffusion effect, by increasing the inter-echo spacing TE during data acquisition, separates water and oil in the T2 domain. Based on the wide local experience, we can assure that the EDM technique works very well for the independent confirmation of oil-bearing zones and identification of oil-water contacts. It is sensitive to oil in the viscosity range from 1 cp to 50 cp and works in areas of unknown or variable Rw.

Time Domain Analysis (TDA) uses NMR data that can be analyzed independently or in combination with conventional logs. When NMR data is processed independently, it provides formation porosity and permeability information, as well as complete information about fluid types and fluid saturation within the depth of investigation of the NMR tool. TDA operates on the principle that different fluids have different rates of polarization or different T1 relaxation times. The T1 of both gas and light oil (viscosity less than 5 cp) is normally much higher than that of water.

TDA effectively evaluates gas and light oil reservoirs and it is different from the other techniques available because it uses only NMR data in the interpretation process; no conventional data is needed in the processing. Interpretation is performed in the time domain rather than in the T2 spectra domain. Some features of TDA analysis include processing echo differences in the time domain using predicted or measured oil, gas, and water relaxation times and hydrogen-index values. TDA provides accurate formation porosity in gas and light oil reservoirs and enables complete fluid volume analysis within the depth of investigation of the NMR tool, using only NMR tool data. TDA also provides hydrocarbon typing; it recognizes direct pay and improves permeability calculations in light hydrocarbon environments.

Propellant-Assisted Perforating Description

The violence of the perforating charge creates a crushed zone around the perforation tunnel. In many formations, underbalanced perforating enables the formation pressures to remove the damaged rock instantly. If the formation pressures are too low to remove the damaged rock, however, the permeability at the face of the perforation can be greatly reduced. PAP is a solution to this kind of problem. The PAP process combines perforating and near-wellbore stimulation using a standard perforating gun and propellant sleeve in a single operation. The potassium perchlorate based propellant is molded into cylinders for easy placement onto a standard perforating gun.

In the case of a previously perforated well, the propellant is normally deployed into the well by wireline or tubing, positioned over the perforated interval, and ignited. As the propellant rapidly burns, high pressure combustion gases are generated. After the tool is spent, the differential pressure is directed toward the wellbore causing a surge into the wellbore. This surging or “back flushing” effect aids cleanup of the near wellbore area.

After positioned on depth, the detonation of the shaped charge contained within the perforating carrier ignites the propellant sleeve. The pressure wave generated by the charge exits through the carrier and penetrates the propellant sleeve and the casing, forming a perforation tunnel in the formation. As the propellant burns, a surge of high-pressure gas is produced that enters the newly created perforation path and breaks through the damage around the tunnel, extending fractures from the perforation (Fig. 3). When gas pressure in the wellbore dissipates, gas surges back, carrying damaging fines from the formation. The back flushing effect has been demonstrated to be further enhanced by perforating underbalanced using the PAP assembly.

Propellant stimulation devices are routinely used for near wellbore clean up and enhancement. One of the primary applications is for perforation breakdown and fracture initiation. Propellant stimulation can be useful after an unsuccessful hydraulic fracture attempt in which formation breakdown cannot be safely achieved. Propellant is used to initiate formation breakdown, enabling a successful fracture reattempt at lower initiation pressures. The PAP technique is used in many different applications with positive results. Those have been documented in many areas in the Gulf of Mexico (Folse et al., 2001), Egypt (Waheed et al., 2001), Algeria (Van Batemburg et al., 2000), Venezuela (Ramirez et al., 2001; Salazar et al., 2002; and Boscan et al., 2005), and Argentina (Elnaga et al., 2007).

Computer simulation software is a very important component of the propellant perforating technique. The output of this software indicates anticipated peak pressure and the degree of fracturing that can be expected. This simulation process provides an essential tool for screening a candidate well for special types of propellant and EOB perforating techniques and for identifying potential operational issues.

In the past, propellant treatments were designed based on experience and field observations. This practice led to less-than- optimum results with occasional reports on actual formation and wellbore damage as a result of overloading the completion with too much energy. The availability of a computer model and high-speed pressure recorders greatly enhanced the ability to understand the propellant-stimulation techniques (Schatz, 1999).

Case Histories

Case History 1. Four application examples are presented from three different wells, PX-908, PX-930, and PX-980. The objective of using PAP was to increase the hydrocarbon production in the selected sand bodies.

The low flow rates obtained from the initial swabbing tests did not confirm the analysis about the reservoir potential and fluid content determined by the use of NMR interpreted logs. Because of the widely acquired experience with NMR logs and the great confidence level achieved on those interpretations, a PAP design program was simulated to maximize the design and use of this technology. The simulator was loaded with the petrophysical information acquired by means of NMR logs and some other information provided by the operator, such as reservoir pressure and Young’s modulus (Table 1). After the simulation, the proper working conditions were determined and the PAP process was recommended for use in these examples. PAP reduces the generated damage induced during well construction (drilling and completion stages).

TABLE 1-CASE 1 MAIN RESERVOIR CHARACTERISTICS				
Formation Data	PX-908	PX-930	PX-980	
Formation	CR	MEC	CR	CR
Perf. Zones [m]	2392.5/96.0	2632.0/34.0 2639.0/43.0	2185.5/88.0 2190.0/97.0	2145.0/47.5
Rock type	Sand	Tuffaceous sands	Sand	Sand
Permeability [mD]	15.0	6.0 – 2.0	0.8 – 15.3	2.0
Porosity [%]	15.5	15.0 – 14.7	12.3 – 17.0	11.0
Pressure [psi]	n/a	n/a	1022.0	2649.0
Young's modulus [psi]	4.3 E+6	4.1 E+6 - 4.25 E+6	4.5 E+6 - 4.7 E+6	4.5 E+6
BHST [°F]	208	222	197	194

All operations were performed in 5 1/2 in casing, 15.5 lb/ft, K-55. The production tubing was 2 7/8in., 6.5 lb/ft, J-55. The perforating gun system used was 3 3/8-in., 6 spf with 22.7 grm. HMX deep penetration plus propellant sleeves.

PX-908. During the completion stage of this well, the reservoir at 2392.5/96 mts. was identified by means of the EDM and TDA interpretation techniques. The composite analysis presentation clearly shows the hydrocarbon content, intermediate OIL viscosity with HGOR fluid content, and good reservoir production potential (petrophysical properties, 15 PU of porosity in Track 3, 60% of oil saturation in track 1, and 15 md of permeability in Track 2) (Fig. 4).

The zone was perforated using a 4-in. gun system, 4spf, 22gr. The initial swabbing test result was DRY. The operator decided to re-perforate the reservoir with a 4-in. gun system, 4spf, 32gr. to try penetrating deeper into the formation. The swabbing test result was DRY again. Based on the reservoir hydrocarbon content and production potential shown by the interpreted NMR log, a PAP simulation was recommended, and a PAP program was designed and performed.

The post PAP swabbing test results showed low flow rate but with high hydrocarbon saturation (low water cut). Based on these results, a hydraulic fracture was designed and performed. After the fracturing operation, the flow rate increased with the same water-cut level (Table 2).

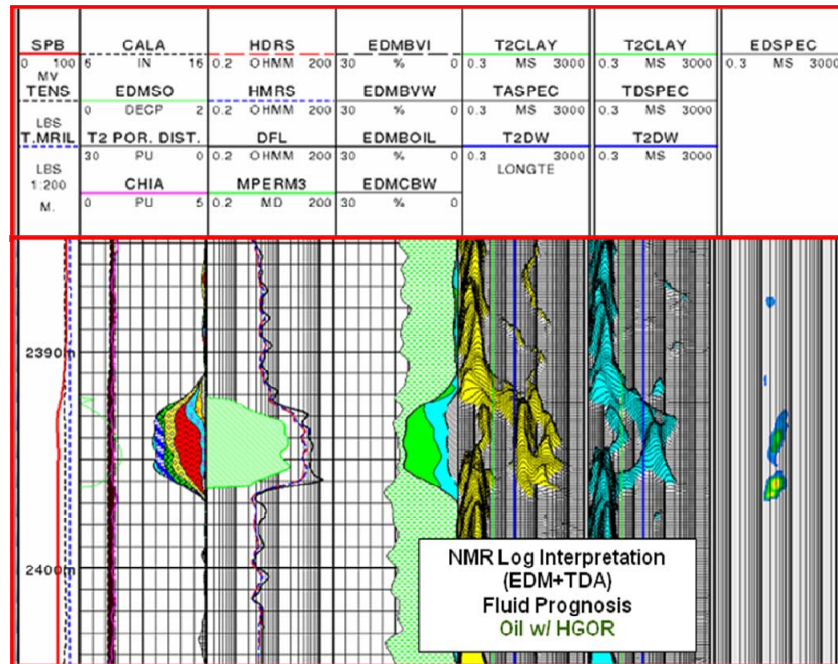


Fig. 3–The Well PX-908 NMR Log Interpretation (EDM+TDA) shows intermediate OIL viscosity with HGOR fluid content. The petrophysical parameters (porosity and permeability) from NMR Interpretation proved good production capacity of the reservoir. After hydraulic fracturing, the reservoir flowed hydrocarbon with low water cut. Track 1 shows Caliper, EDM Oil saturation and T2 distribution bins from NMR Log. Track 2 presents resistivity and permeability from the NMR Log (EDM Analysis). Track 3 presents Fluid Volume Analysis from EDM. Tracks 4 and 5 show the Short-Te and Long-Te T2 distributions from EDM. Track 6 shows the TDA T2 difference spectrums.

TABLE 2–CASE 1 SWABBING TEST RESULTS FROM THE DIFFERENT STAGES (CONVENTIONAL PERFORATING, PAP AND HYDRAULIC FRACTURE) DURING THE COMPLETION OF THE RESERVOIR						
PX-908 Swabbing Tests						
Operation	Rate Fluid lt/h	Rate Oil lt/h	Rate Water lt/h	BWS %	Level m	Salt ppm
Conventional Perforating 22 gr	Dry fluid					
Conventional Perforating 32 gr	Dry fluid					
After PAP	520	364	156	30	2197	7500
After Fracture Hydraulic	1200	744	456	38	2170	5600

PX-930 and PX-980. As in the previous example, the initial low flow rate swabbing test results of the perforated zones, by the use of the conventional perforating systems, disagreed with the NMR interpretation in terms of hydrocarbon content and production capacity. In addition, correlation with nearby wells confirmed the good hydrocarbon production potential of those reservoirs. The PAP objective was to increase the production, while maintaining the cost/benefit ratio (Table 3).

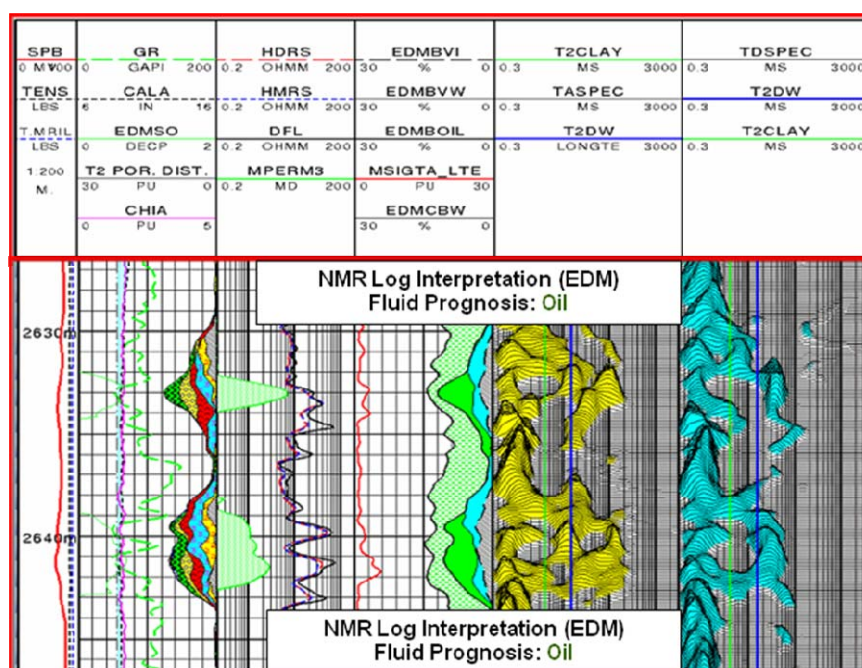


Fig. 4–The Well PX-930 NMR Log Interpretation (EDM) shows intermediate OIL viscosity. The petrophysical parameters (porosity and permeability) from the NMR Interpretation proved good production capacity of the reservoir. After the PAP application, the reservoir flowed hydrocarbon. Track 1 shows Caliper, EDM Oil saturation and T2 distribution bins from NMR Log. Track 2 presents resistivity and permeability from the NMR Log (EDM Analysis). Track 3 presents Fluid Volume Analysis from EDM. Tracks 4 and 5 show the Short-Te and Long-Te T2 distributions from EDM.

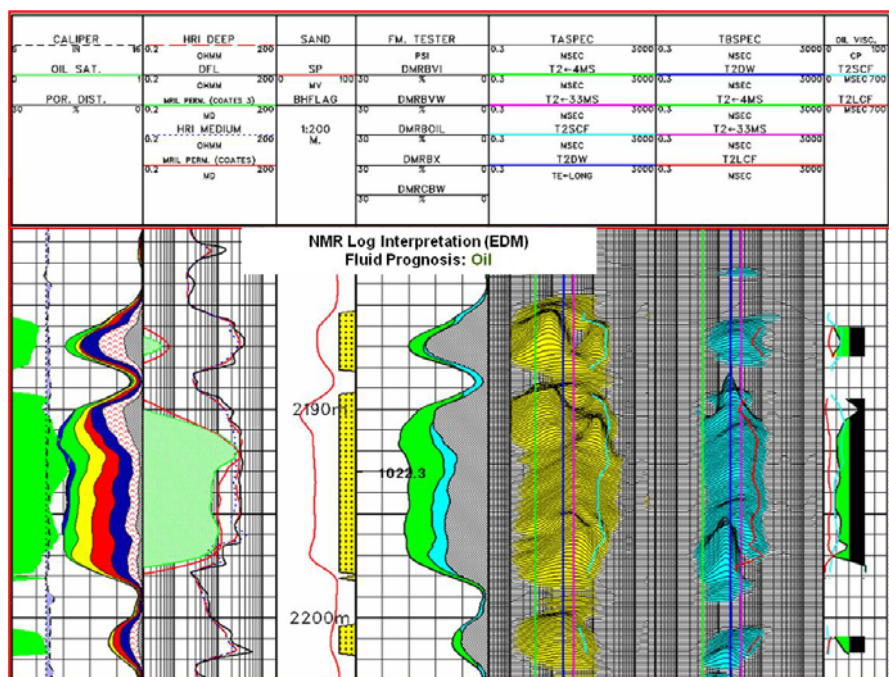


Fig. 5–The Well PX-980 NMR Log Interpretation (EDM) shows intermediate OIL viscosity. The petrophysical parameters (porosity and permeability) from NMR Interpretation proved good production capacity of the reservoir. After the PAP application, the reservoir flowed hydrocarbon. Track 1 shows Caliper, EDM Oil saturation and T2 distribution bins from NMR Log. Track 2 presents resistivity and permeability from the NMR Log (EDM Analysis). Track 3 presents Fluid Volume Analysis from EDM. Tracks 4 and 5 show the Short-Te and Long-Te T2 distributions from EDM.

TABLE 3–CASE 1 SWABBING TEST RESULTS FROM THE DIFFERENT STAGES (CONVENTIONAL PERFORATING AND PAP) DURING THE COMPLETION OF THE RESERVOIRS IN TWO DIFFERENT WELLS							
Well	Conventional Perforating			Propellant-Assisted Perforating			Fluid Increase
	Rate lt/h	Water %	Oil m3/day	Rate lt/h	Water %	Oil m3/day	
PX-930	220	100	0	940	70	6.8	4.3
PX-980 (2185.5 m)	120	100	0	600	100	0.0	5.0
PX-980 (2145.0 m)	450	100	0	1800	72	12.1	4.0

Case History 2. In multi-layer reservoirs, hydrocarbon bearing zones and water bearing zones are often located only a few meters apart (2 to 10 m). The hydrocarbon bearing zones cannot be stimulated by hydraulic fracturing because of the proximity to the water reservoirs (Fig. 6, Fig. 7). The NMR interpretation log made it possible to distinguish oil bearing zones from water zones. The nearby well correlation is also analyzed. This information and other information delivered by the operator company is compiled and loaded on the simulator for proper PAP application (Table 4).

TABLE 4–CASE 2 MAIN RESERVOIR CHARACTERISTICS					
Formation Data	PX-873	PX-1026	PX-865	PX-1002	PX-1231
Formation	CR	CR	CR	CR	MEC
Distance to Water Zone [m]	5.0	5.0	4.0 - 6.5	3.5	8.0
Perf. Zones [m]	1828.5/34.0	1819.5/22.0 1828.0/35.0	1033.5/36.5 1050.0/53.0 1071.0/73.5	1819.0/21.	760.5/63.5 764.5/67.0
Rock Type	Sand	Tuffaceous Sands	Sand	Tuffaceous Sands	Sand
Permeability [mD]	7.0	9.0 - 16.0	8.0 - 2.0 - 4.0	2.0	25.0 - 38.0
Porosity [%]	20.0	14.2 - 16.5	21.0 - 18.0 - 20.0	18.0	24.0 - 26.0
Pressure [psi]	2400.0	2519.0	1100.0	2374.0	900.0
Young's modulus [psi]	4.2 E+6	4.4 E+6 4.5 E+6	4.0 E+6 4.15 E+6 4.1 E+6	4.5 E+6	5.2 E+6 5.6 E+6
BHST [°F]	177	176	125	176	117

The zones were perforated using conventional perforating (4-in. gun system, 4spf, 22gr.) The initial swabbing test results (Table 5) showed that the reservoirs were candidate to stimulation.

After running the hydraulic fracture simulator it was concluded that the fracture height would contact the water with the hydrocarbon reservoir. To do so, an alternative to increase production was to apply the PAP technique, minimizing water production risk.

All operations were performed in wells cased with 5 1/2 in. casing, 15.5 lb/ft, K-55. The production tubing was 2 7/8 in., 6.5 lb/ft, J-55. The perforating gun system used was 3 3/8 in., 6 spf with 22.7 grm. HMX deep penetration plus propellant sleeves.

The five applications documented for this case were performed in the following wells: PX-873, PX-1026, PX-865, PX-1002, and PX-1231. Not only did post-PAP trials indicate an important increase in the whole fluid flow rate, but the water cut was also significantly diminished in four wells (Table 5).

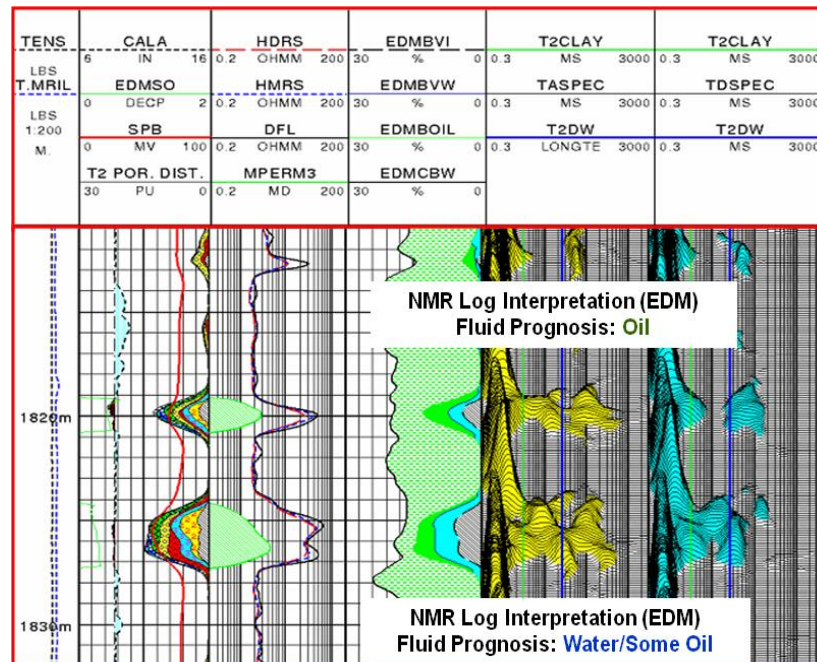


Fig. 6–The Well PX-1002 NMR Log Interpretation (EDM) shows intermediate OIL viscosity in the upper reservoir and water at the bottom reservoir. The petrophysical parameters (porosity and permeability) from NMR Interpretation proved medium to good production capacity of the reservoir. After the PAP application, the reservoir flowed hydrocarbon. Track 1 shows Caliper, EDM Oil saturation and T2 distribution bins from NMR Log. Track 2 presents resistivity and permeability from the NMR Log (EDM Analysis). Track 3 presents Fluid Volume Analysis from EDM. Tracks 4 and 5 show the Short-Te and Long-Te T2 distributions from EDM.

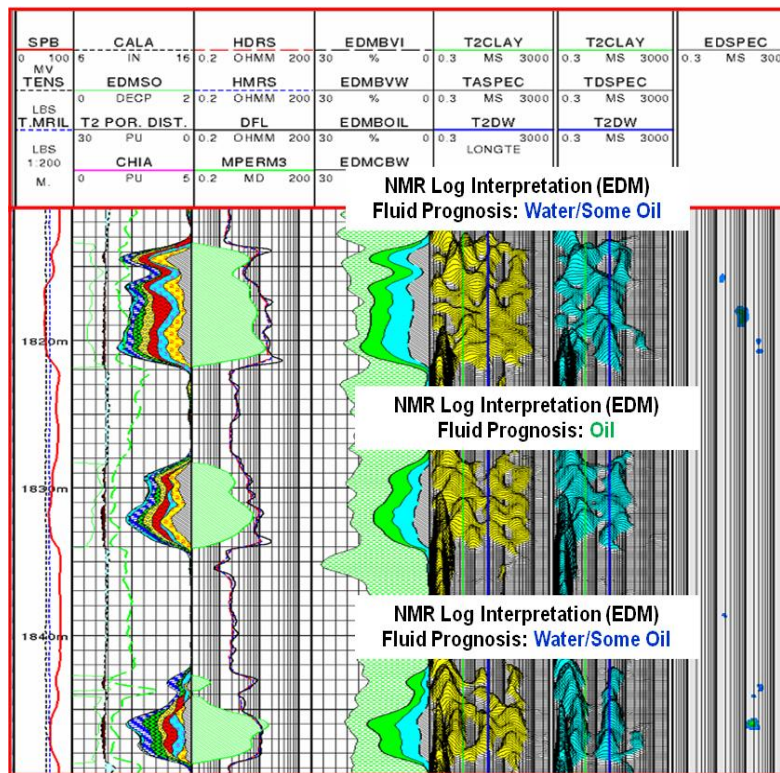


Fig. 7–The Well PX-873 NMR Log Interpretation (EDM+TDA) shows intermediate OIL viscosity fluid content. The petrophysical parameters (porosity and permeability) from NMR Interpretation proved good production capacity of the reservoir in the middle of the section. The upper and lower reservoirs clearly contain water. After the PAP application, the reservoir flowed hydrocarbon with some water. Track 1 shows Caliper, EDM Oil saturation and T2 distribution bins from NMR Log. Track 2 presents resistivity and permeability from the NMR Log (EDM Analysis). Track 3 presents Fluid Volume Analysis from EDM. Tracks 4 and 5 show the Short-Te and Long-Te T2 distributions from EDM. Track 6 shows the TDA T2 difference spectra.

TABLE 5–SWABBING TEST RESULTS FROM THE DIFFERENT STAGES (CONVENTIONAL PERFORMING AND PAP) DURING THE COMPLETION OF THE RESERVOIRS IN DIFFERENT WELLS							
Well	Conventional Perforating			Propellant-Assisted Perforating			Fluid Increase
	Rate lt/h	Water %	Oil m3/day	Rate lt/h	Water %	Oil m3/day	
PX-873	220	100	0.0	1800	65	15.1	8.2
PX-1026	624	50	7.5	1196	28	20.7	1.9
PX-865	351	90	0.8	728	92	1.4	2.1
PX-1002	344	65	2.9	780	10	16.8	2.3
PX-1231	390	60	3.7	1080	30	18.1	2.8

Case History 3. The goal of the PAP application in this case was to diminish the fracture pressure. In the field where this technique was used, there was previous information about a well located 300 m away in which the reservoir was perforated with conventional charges (4 in., 6 spf with 32 g) in the same interval. After perforating conventional with out propellant, the pumping diagnostic was performed and a fracture gradient (0.89 psi-ft) was detected, which caused the stimulation abortion as a result of the elevated work pressure. The case we will document belongs to well PX-1008 (Fig. 8), which was perforated in a conventional way. After performing the minifrac, a fracture gradient of 0.87 psi-ft was determined; this one being a similar situation to the previous one.

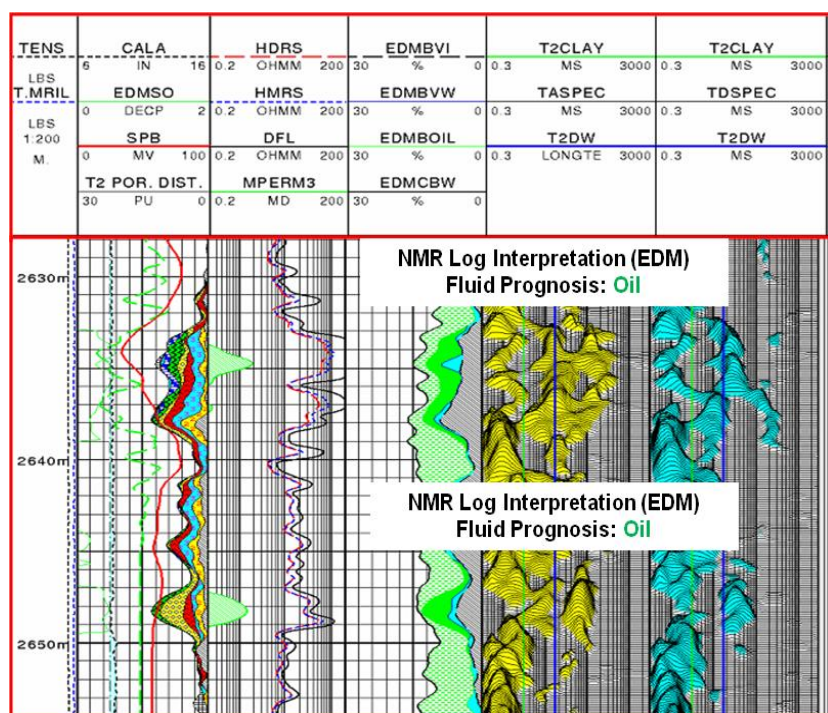


Fig. 8–The Well NMR Log Interpretation (EDM) shows intermediate OIL viscosity in the upper reservoir, and water at the bottom reservoir. The petrophysical parameters (porosity and permeability) from NMR Interpretation proved poor production capacity of the reservoir, so a hydraulic fracture was recommended. After the PAP application, the reservoir was fractured and it flowed hydrocarbon. Track 1 shows Caliper, EDM Oil saturation and T2 distribution bins from NMR Log. Track 2 presents resistivity and permeability from the NMR Log (EDM Analysis). Track 3 presents Fluid Volume Analysis from EDM. Tracks 4 and 5 show the Short-Te and Long-Te T2 distributions from EDM.

Considering the operator’s interest in stimulating the reservoir, the service company recommended the use of the PAP method to diminish the work pressure and enable the performance of the operation.

Table 6 provides information about the well, formation, and PAP. This information was used to perform the computer-aided simulations (Fig. 9).

TABLE 6–CASE 3 MAIN RESERVOIR CHARACTERISTICS AND PAP DATA	
Formation Data	
Reservoir	Oil-Gas
Rock type	Tuffaceous Sands
Permeability [mD]	1
Porosity [pu]	15
Reservoir Pressure [psi]	3600
Young’s Modulus [psi]	4.5 e+6
BHST [°F]	223
Perforated Zones [m]	2633.0/38.0 - 2647.0/49.5
Well Data	
Casing	5 1/2" - K55 - 15.5 lb/ft
Tubing	2 7/8" - J55 - 6.4 lb/ft
PAP Data	
System Gun	3 3/8"
Charge	22.7 gr.
Spft	6
Propellant	6 ft - 6 ft
Fracture Length	7.21 ft - 9.75 ft

Summary Report
File Name: Stim_Gun_TCP_Intv2633to2649.5m.pul
Run Date: 6/21/2008
Output Date: 6/21/2008

Results for Working Region #1:

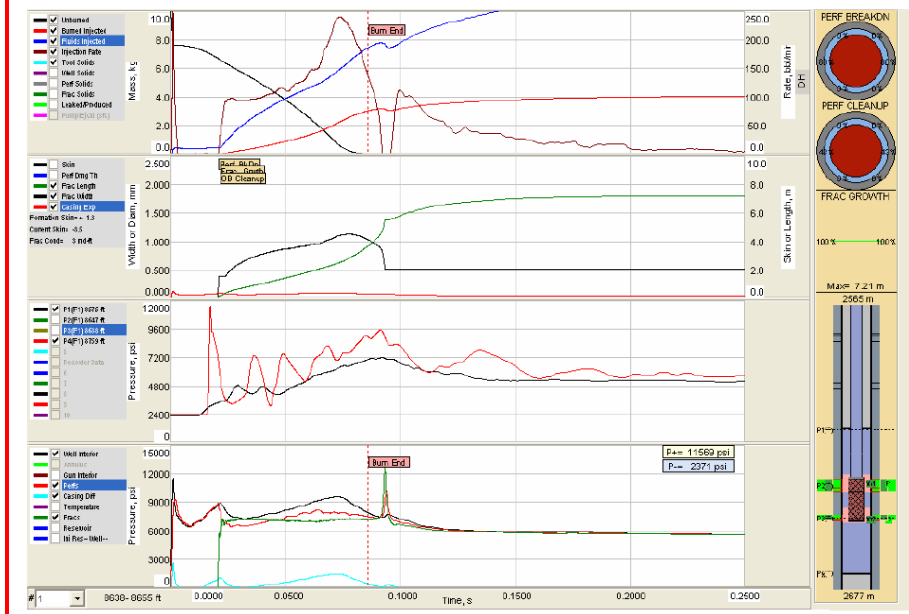


Fig. 9-PAP computer-aided simulation.

After applying the PAP technique, the hydraulic fracture was performed with the designed pumping pressure and a reduction in the working pressure. The information is provided in Table 7 and in Fig. 10 and Fig. 11.

TABLE 7-REDUCED HYDRAULIC FRACTURE PUMPING RATE AND WELLHEAD PRESSURE USING THE PAP TECHNIQUE

	Minifrac	Hydraulic Fracture
Pumping Rate [bpm]	11.8	15.3
Wellhead Pressure [psi]	6800	6515
Fracture Fluid	Lineal Gel	Guar (Borate)

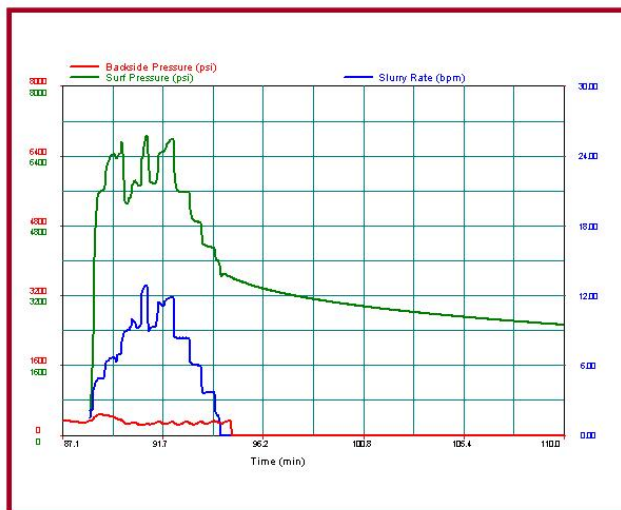


Fig. 10-Minifrac

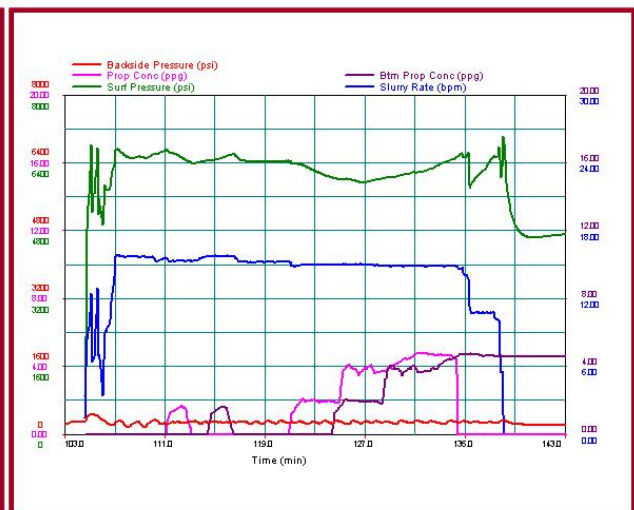


Fig. 11-Hydraulic fracture

Conclusions

The use of the PAP method in the San Jorge basin resulted in the following:

- The fluid content and the production reservoir capacity were proven by means of the NMR Log interpretation (EDM and TDA); the results had not been achieved with the use of conventional perforating methods.
- Zones with good hydrocarbon prognosis, though with low flow production rates when applying the PAP technique, have shown increases on a 400% fluid average.
- Hydrocarbon zones that were unable to be stimulated because of nearby water zones have increased the hydrocarbon production.
- Zones that were unable to be fractured because of a high fracture gradient were successfully stimulated.

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