Hydraulic fracture assisted with coiled tubing in unconventional wells: lessons learned and case histories from northern Mexico

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Abstract

Deviated wells are commonly used for exploiting hydrocarbons in very low permeability and unconventional reservoirs in northern Mexico. These wells require more sophisticated drilling and completion methods and special techniques and logistics, with an inherent learning curve used by every region or location, to obtain the expected results for these projects.

To achieve better performance when fracturing multiple zones, using an abrasive perforating technique with coiled tubing (CT) has proven to be very effective. This is especially true for applications in highly deviated and horizontal wells. Although this technique has been used since 1998, implementation in the region discussed in this paper has only been common for the past three years.

This paper discusses field experiences and case histories that illustrate the use of new technologies and techniques for this region, which resulted in successful completions. The diversity of applications and better operational performance provided by CT were important for completing the jobs, and the abrasive perforation process was key for allowing the use of hydraulic fracturing as a major component in the production of these wells.

Keywords: Hydraulic fracture, abrasive drilling, abrasive shots, coiled tubing.

Fracturamiento hidráulico en múltiples etapas asistidas con perforaciones abrasivas en pozos altamente inclinados y horizontales: lecciones aprendidas y casos históricos del norte de México

Resumen

Los pozos desviados han sido una opción común para explotar hidrocarburos en yacimientos de muy baja permeabilidad y en los no convencionales en el Norte de México. La perforación y la terminación son ahora más sofisticadas y requieren de técnicas especiales y de una logística especial, que cada región o localidad tiene que aplicar hasta que su curva de aprendizaje indique que ha llegado el momento y el éxito de estos proyectos.

Con el fin de lograr un alto rendimiento en los fracturamientos hidráulicos en varias zonas, la aplicación de la técnica de disparos abrasivos con tubería flexible ha demostrado ser una alternativa muy efectiva para adquirir resultados incuestionables. Esto ha sido especialmente cierto en cuanto a la aplicación en pozos altamente desviados y horizontales, que, a pesar de que es una técnica aplicada desde 1998, la implementación en la región ha sido más corriente en los últimos tres años.

El siguiente artículo mostrará, a través de la experiencia en campo de casos reales, las tecnologías disponibles y las técnicas que resultaron como nuevos procesos en esta región. Estos esfuerzos han resultado en un gran logro en este tipo de terminación de pozos. La diversidad que ofrece la tubería flexible y el desempeño logrado han sido significativamente importantes para completar los trabajos de una manera exitosa. El proceso de perforación abrasiva ha sido una tecnología de gran importancia para que el fracturamiento hidráulico sea exitoso como componente principal en los resultados de producción en estos campos, características petrofísicas similares en la misma formación y usando el mismo volumen de apuntalantes.

Palabras clave: Fracturamiento hidráulico, perforaciones abrasivas, disparos abrasivos, tubería flexible.

Introduction

The challenges faced by operators to perform the final completion of a deviated well are tied to many factors. In the Burgos basin, many drilled wells require hydraulic fracturing to improve permeability, so that hydrocarbons—in this case, dry and wet gas—can flow. Making matters more complex, this type of well construction requires multiple fractures that connect at different points in these very tight reservoirs.

The perforation strategy might be the most important variable in this type of completion, because the effectiveness of the stimulation treatment is directly correlated with this process. To make the connection between the reservoir and the wellbore, there are several techniques that can be used, ranging from conventional wireline perforating, tubing conveyed shape charge perforating (TCP), and hydrajet perforating (either tubing deployed or CT deployed). With conventional wireline perforating, there are limitations when used in high-angle wells with deviation, and the execution time and logistics required can be prohibitive. The use of other techniques, such as TCP, can also require long operating times. Recently, the use of the plug-and-perf technique (with pump-down plugs dragging wireline perforation guns) has solved many of these problems concerning logistics and speed. However, making the first perforated interval requires a device that can be moved slowly and precisely along the pipe (typically CT or tractor).

CT can be used to meet several objectives. In the past, these objectives required a significant investment in time and money. Versatility in achieving precise programmed depths, makes this technology one of the most important for maximizing the potential of an operation.

The hydrajet assisted fracturing (HJAF) technique was conceived by Dr. Jim Surjaatmadja. When the hydrajet perforating technique was first implemented in 1994 (Surjaatmadja et al. 1994), perforations or holes were created by pumping an abrasive mixture of fluid and sand through CT. A jet nozzle was then focused on a single point and generated enough energy to cut through the metal. An abrasive perforation is simple and only requires an injecting device adjacent to the metal and abrasive fluid—linear gel and sand—to be pumped through it with a differential pressure ranging from 1,200 to 3,000 psi. The eroding process to create the perforation tunnels can take 5 to 10 min. For this first implementation, the CT was removed for pumping the fracturing treatment that followed.

In 1998, the hydrajet perforating application and hydraulic fracturing were combined into a single well intervention to place distinct hydraulic fractures at multiple locations in horizontal wells (Surjaatmadja 1998; Surjaatmadja et al. 1998). This process is most commonly referred to in the literature as HJAF.

Fig. 1 shows cutting being performed on a 5 1/2 in. cemented casing inside another 9 5/8 in. casing. The time required to get through the 9 5/8 in. tubing was less than 3 min, and the hole made with the 1/4 in. jet was almost 1 in. in diameter (East et al. 2008). This kind of perforation is very difficult to duplicate with conventional explosive charges.

Fig. 2 shows the erosion pattern of abrasive jetting on a cemented casing and a sandy rock. It is important to consider that, even though the perforation diameter on the steel is close to 1 in., on eroding rock this value would be doubled. Thus, the resulting conductivity for fracturing and production is much higher.

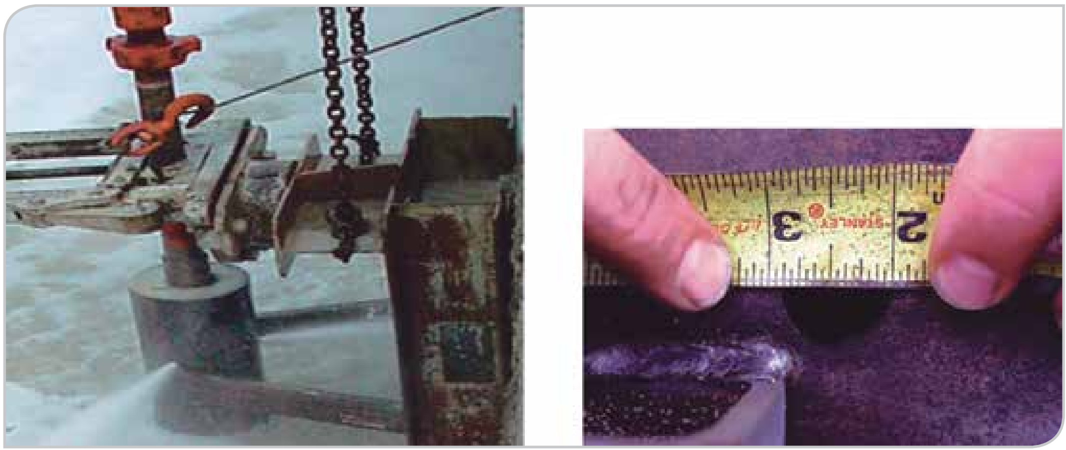

Fig 1. Cutting performed on 5 1/2 in cemented casing.

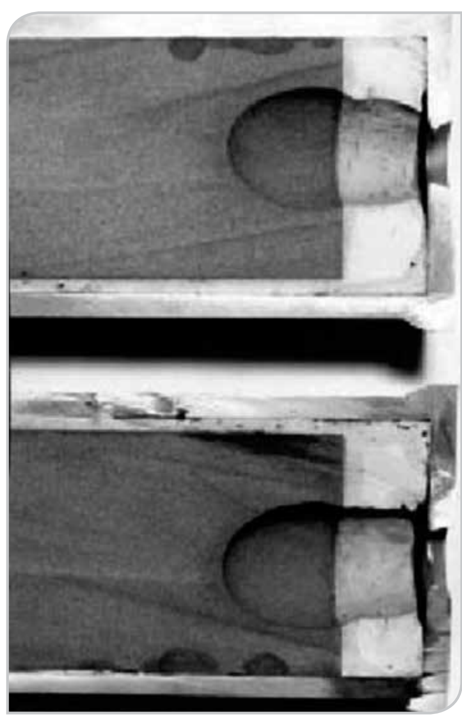

Fig. 2. Erosion pattern of abrasive jetting.

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In 2002, a new implementation that used CT deployed perforating followed by pumping the fracturing stage down the casing-CT annulus was developed (Surjaatmadja et al. 2005). The fracturing operations completed during the treatment also used isolation with sand plugs for each stage, and this was repeated at multiple locations as the process moved up the wellbore, with the CT remaining in the well for the entire multistage fracturing operation. This process was first used in vertical well applications and later in horizontal wells (East et al. 2008). In the literature, this application has been labeled as hydrajet perf annulus fracturing or HJAF process. **Fig. 3** shows the stage sequence; a simplified fracturing process was achieved because of the time savings and versatility that CT provided.

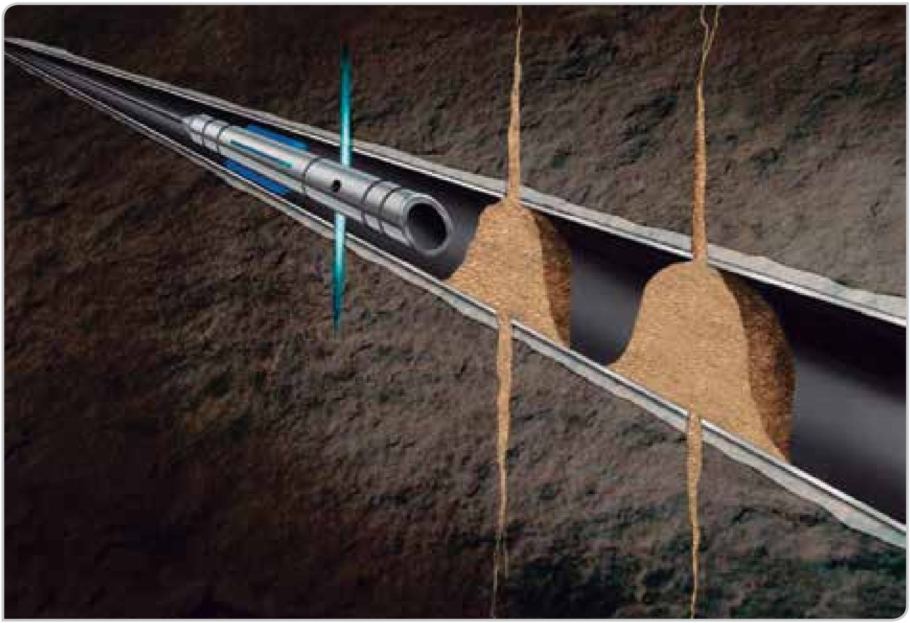

Fig. 3. Sand plugs for staging sequence.

A bottomhole assembly basically consists of four pieces for the execution of such operations, **Fig. 4**. A typical equipment layout is shown in **Fig. 5**.

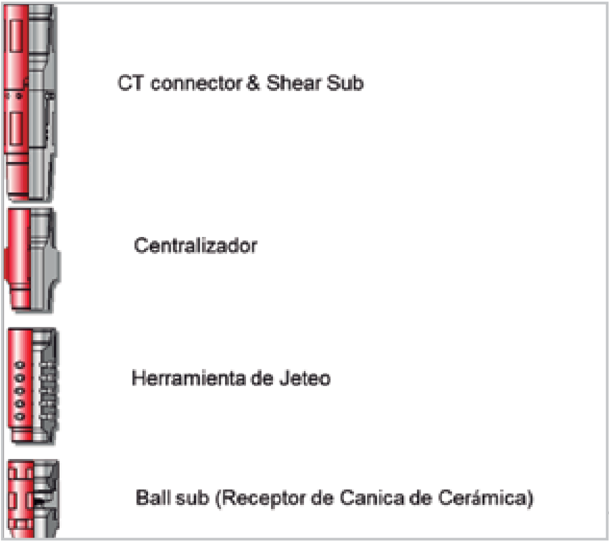

Fig. 4. Typical hydrajetting tool details.

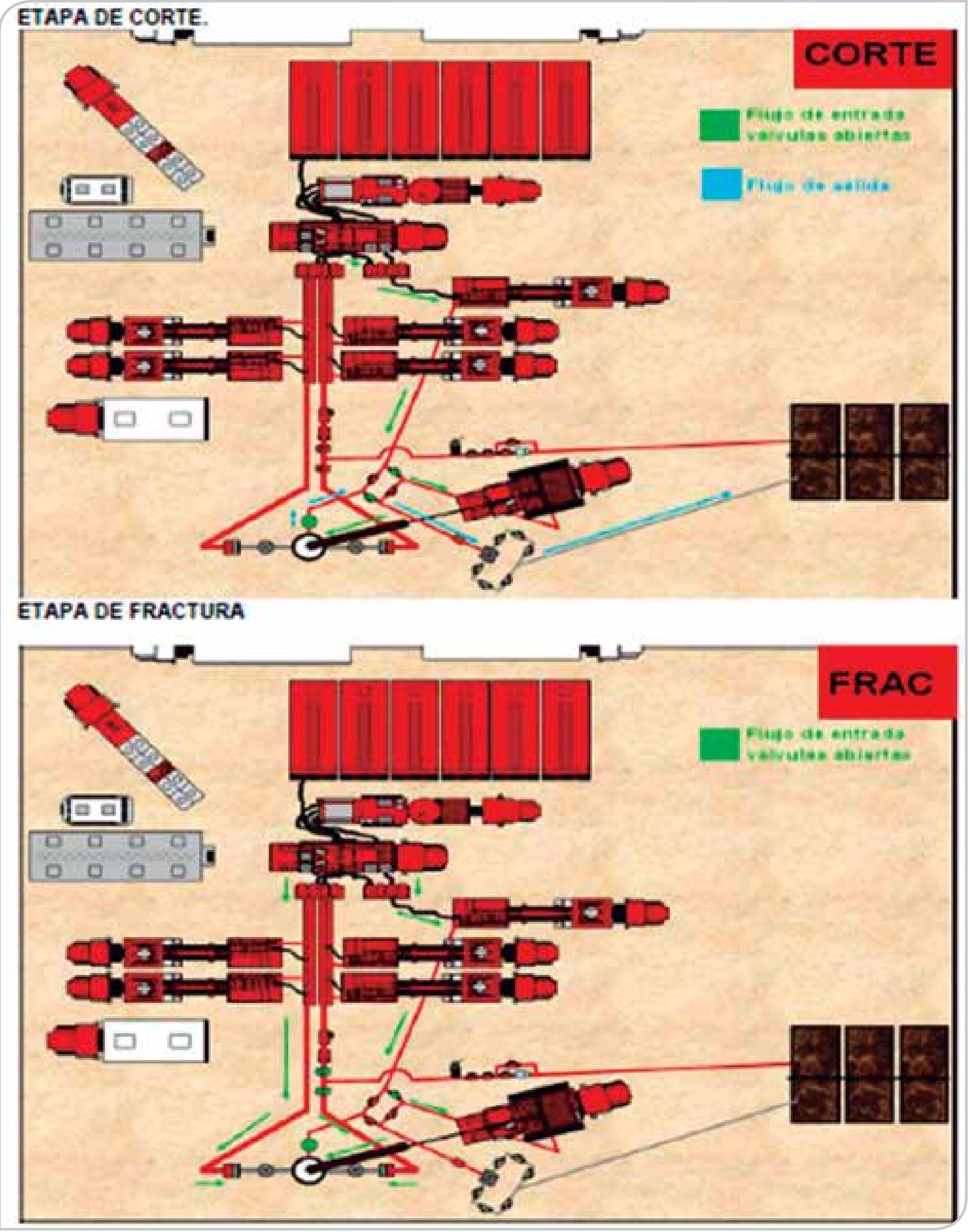

Fig. 5. Typical configuration for performing HJAF with abrasive perforating.

Benefits of HJAF

The following benefits are provided using the HJAF technique:

- Several trips are not required down hole to create the perforations.
- Damaged, compacted perforation tunnels are non-existent.
- Lower initiation fracture pressures are observed.
- Near-wellbore (NWB) tortuous fractures are eroded.

- A fracture with dominating energy is established.
- Low downhole treatment pressures are observed.
- High proppant concentrations are achieved.

Cases histories in Burgos basin in northern Mexico

This study includes a review of several operations using deviated and horizontal wells. In total, there were five wells in which HJAF was performed. In the last two years, 50 hydraulic fracturing stages were performed, which included wells in gas-oil shales and tight sandstones.

Case 1: Highly Deviated Well, Formation PM-10. Challenges encountered in this well, **Fig. 6**, include the following:

- Multiple fractures were required to place perforations into a zone of tight gas with an inclination of 72°.
- Limited hours of operation.

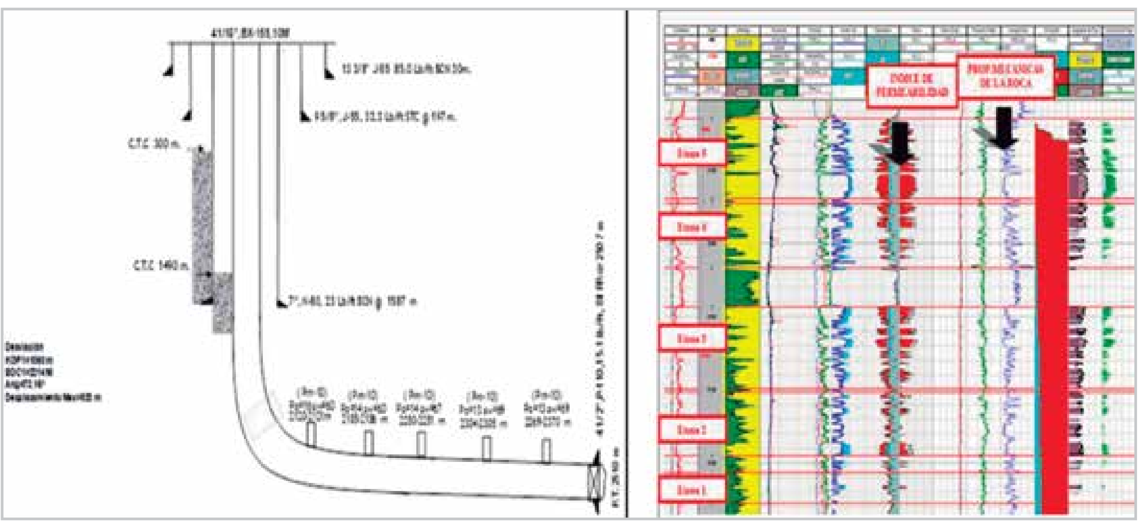

Fig. 6. Case 1 well characteristics.

This well was completed with a 4 1/2 in. cemented casing, P-110, 15.1 lb/ft, at 2,510 ft measured depth (MD) (1940 m true vertical depth [TVD]), with a lateral length of 400 m. The main reservoir characteristics showed bottomhole pressure (BHP) = 3,817 psi, k = 0.09 md, and ϕ = 12%. Ten abrasive perforations were performed in five clusters (2362 to 2363 m; 2304 to 2305 m; 2250 to 2251 m; 2180 to 2181 m; and 2120 to 2121 m).

The operation also consisted of cleaning the well, calibrating with a gamma ray casing collar locator (GR-CCL) logging, and placing sand plugs at the end of each fracture stage.

Fig. 7 shows one of the perforation stages, in which the drops in pressure when the abrasive fluid performed its function are clearly shown at the required depth. For this well, the completion was made with 1 3/4 in. CT and a 3 1/16 in., 60°, 6 spf jetting tool.

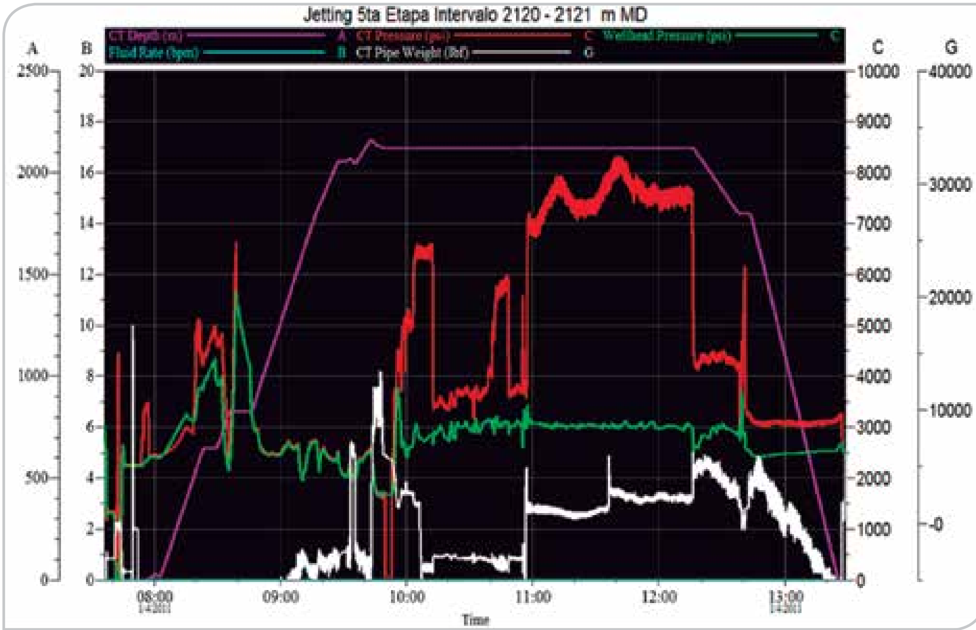

Fig. 7. One of the five perforating stages performed on the well.

Multistage hydraulic fractures, according to the completion plan, were also performed. Details of an example stage are shown in **Fig. 8**.

A total of 901,000 lbm of 20/40-mesh resin coated proppant was pumped, with an average of 180,000 lbm per stage at a rate of 30 bbl/min. The maximum proppant concentration achieved was 9 lbm/gal. The total volume of crosslinked gel used was 8,400 bbl.

The recorded production of the well was six MMcfd with a wellhead pressure (WHP) of 3,500 to 4,000 psi.

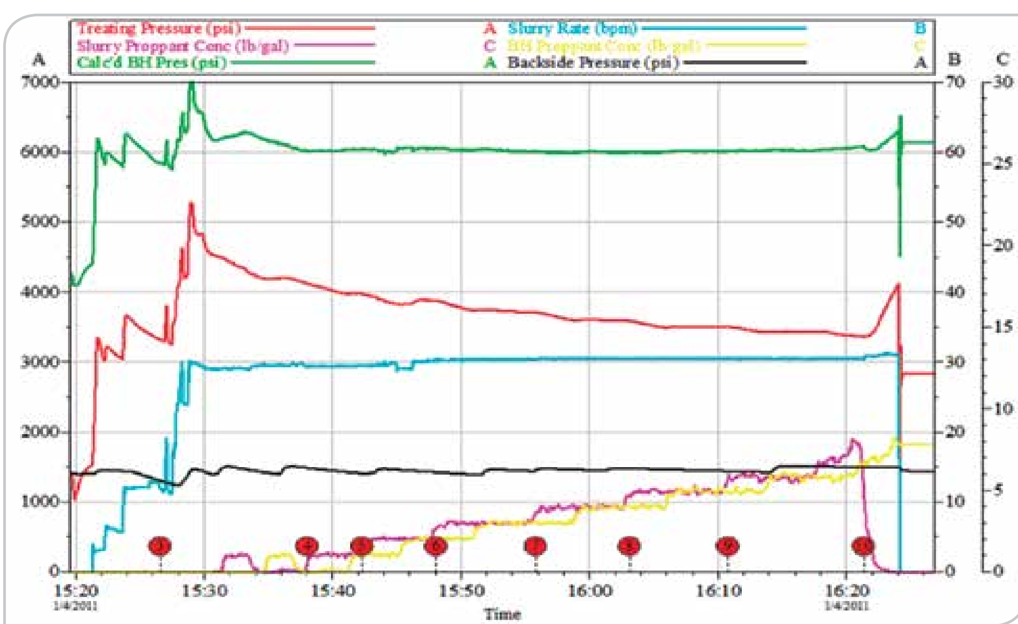

Fig. 8. Example of the multistage hydraulic fractures performed.

Case 2: Horizontal Well, E Yegua Slump Formation. The challenges encountered in this well, **Fig. 9** include the following:

- Horizontal tight gas well (89° deviation).
- The need to place multiple fractures spaced unevenly along a 288 m lateral length.

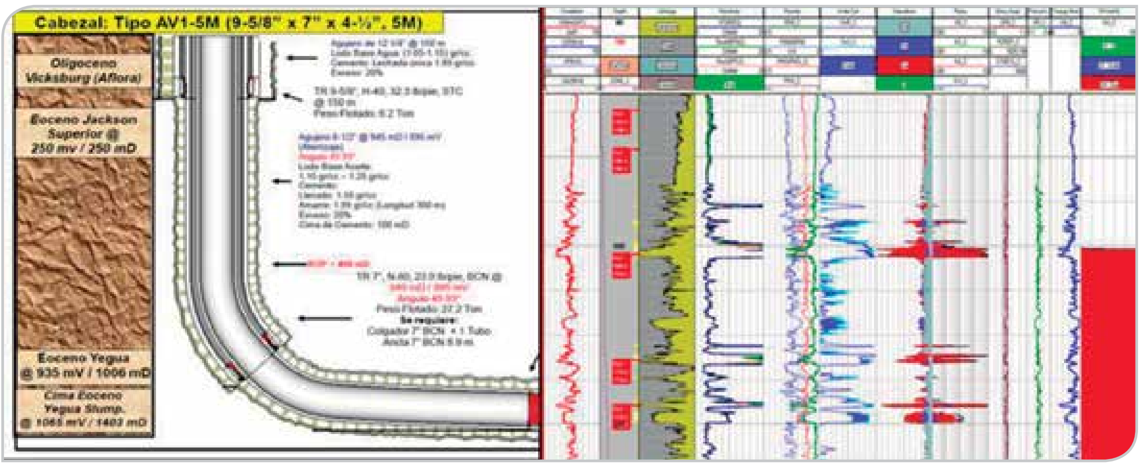

Fig. 9. Case 2 well characteristics.

This well was completed with a 4 1/2 in., P-110 ,15.1 lb/ft, casing at 1851 m MD (1065 m TVD). Formation parameters were BHP = 2,400 psi, k = 2.05 md, and ϕ = 23%. A total of 14 abrasive perforations along five clusters were completed (1778 to 1780 m; 1724 to 1725 m; 1609 to 1610 m; 1486 to 1496 m, and 1443 to 1454 m MD).

The operations began with a cleaning stage using mill bits and calibration with GR-CCL logging on memory. Isolation was performed with sand plugs at the end of each fracturing stage.

Fig. 10 shows the abrasive perforation of two of the intervals with a 9 m space between them. For this well, 1 3/4 in. CT was used with a 3 1/16 in., 120° phase, 3 spf jetting tool.

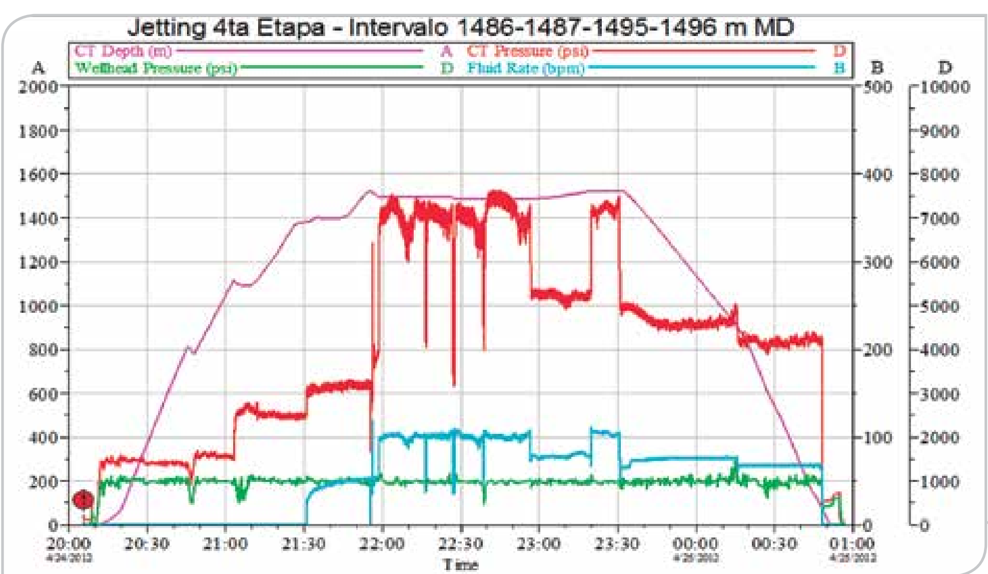

Fig. 10. Abrasive perforation of two of the intervals in case 2.

Multistage hydraulic fracturing Job. **Fig. 11** shows that a certain amount of friction at the beginning of the fracture was observed, which was corrected using sand sweeps pumped during the pad stage. At the end of the proppant ramp, a high-concentration sand plug (15 lbm/gal) placed to isolate the stage can be verified.

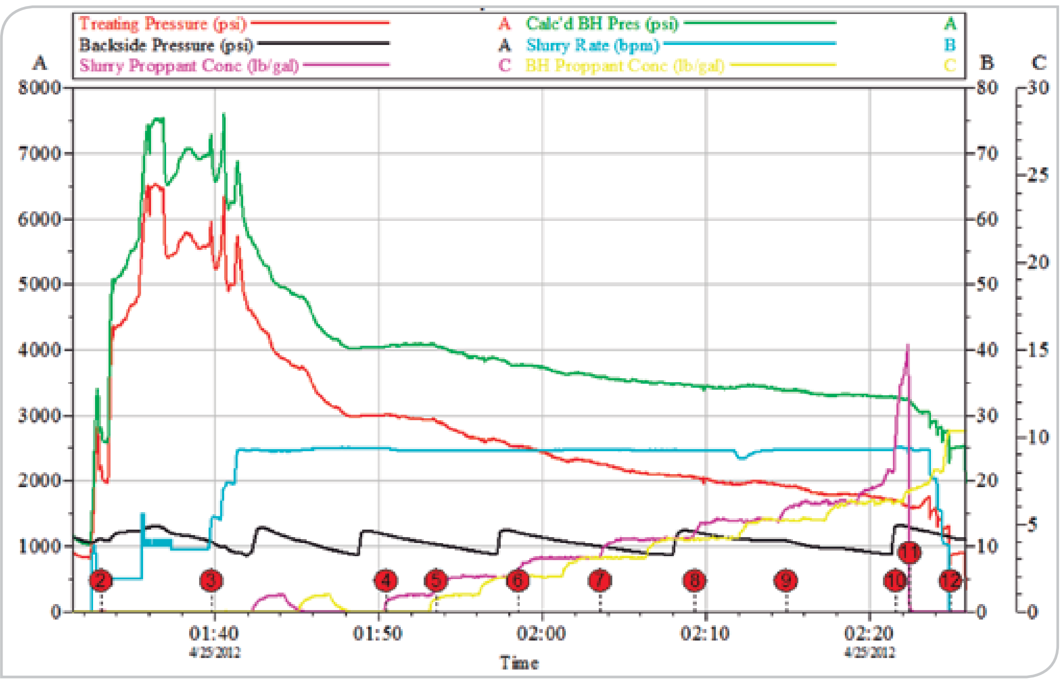

Fig. 11. Example of one of the case 2 stages of the multistage fracturing treatment.

A total of 750,000 lbm of 16/30-mesh sand was pumped. An average of 150,000 lbm per stage was pumped at a rate of 25 bbl/min, and the maximum proppant concentration achieved was 10 lbm/gal. The total crosslinked gel fluid used was 6,300 gal. The recorded production of the well was of 1.9 MMcfd of gas with a WHP of 1,400 to 1,500 psi.

Case 3: Horizontal Well, E Yegua Slump Formation. The following challenges were observed in this well, **Fig. 12**:

- It was a horizontal tight gas well.
- There was a need to place multiple fractures at unequal spacing along a 510 m lateral length.
- The formation had post-fracture sand production.

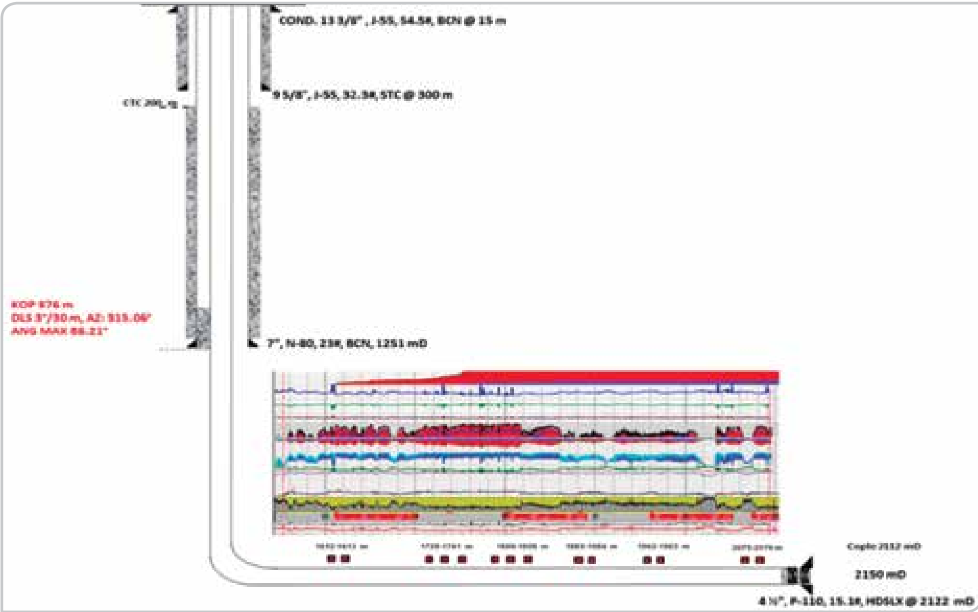

Fig. 12. Case 3 well characteristics.

This well was completed with a 4 1/2 in., P-110, 15.1 lb/ft, casing at 2122 m MD (1300 m TVD). Formation parameters were BHP = 2,700 psi, k = 0.227 md, and ϕ = 12%. A total of 14 abrasive perforations along six clusters were executed (2075 to 2076 m; 1962 to 1963 m; 1883 to 1884 m; 1800 to 1806 m, 1735 to 1741 m, and 1612 to 1613 m MD).

As in the other completions, the operations began with a cleaning trip using a mill, followed by a GR-CLL calibration log, **Fig. 13**. This operation was performed with the goal of achieving a precisely correct depth.

Fig. 14 shows the abrasive perforating for Stage 3 with three intervals spaced 3 m apart. The completion was performed using 1 3/4 in. CT with a 3 1/16 in. jetting tool, 120° phase, 3 spf.

Fig. 15 shows an example stage of the multistage hydraulic fracture showing an optimized fluid stage and the liquid resin pumped in the last 500 sec of sand in the stage.

A total of 1,513,000 lbm of 16/30–mesh sand was pumped, with an average of 250,000 lbm per stage at 35 bbl/min, with a maximum concentration of 10 lbm/gal. 10,000 bbl of crosslinked gel were used. The recorded production of the well was 13 MMcfd of gas, 500 bbl/day of oil, and a WHP of 2,250 psi.

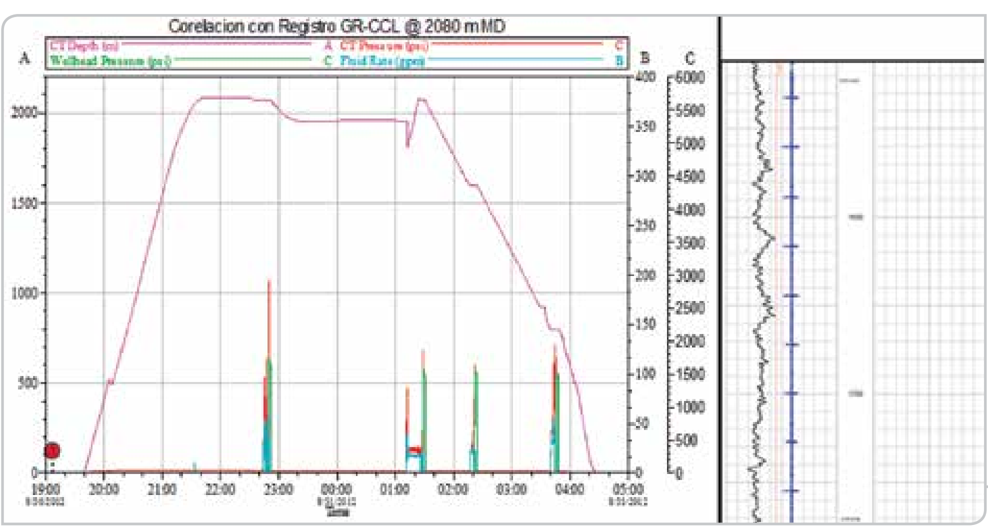

Fig. 13. GR-CCL calibration and calibration log.

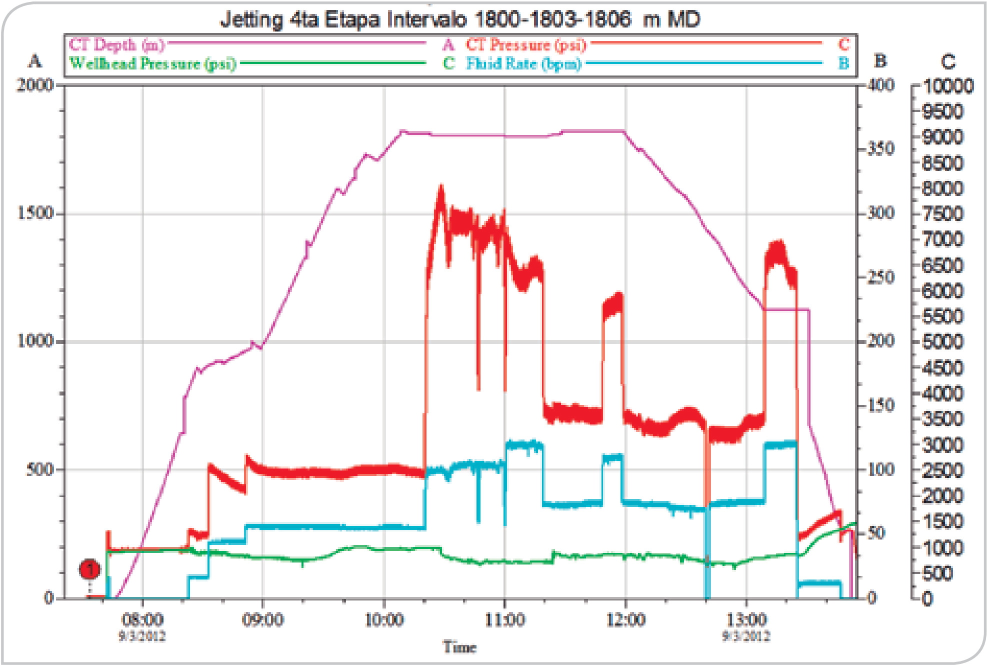

Fig. 14. Abrasive perforation stage.

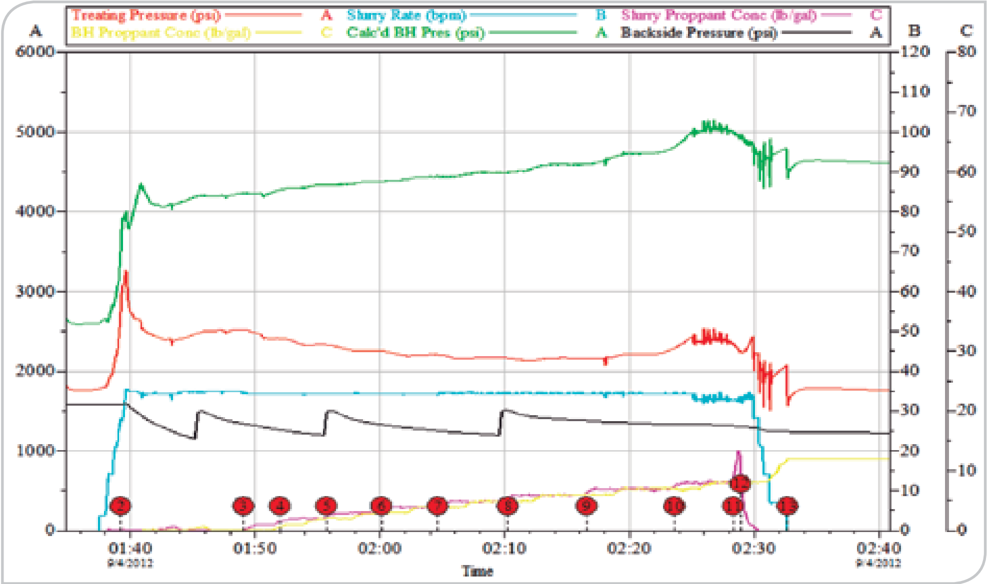

Fig. 15. Example of hydraulic fracture showing an optimized fluid stage and the liquid resin pumped.

Case 4: Horizontal well, gas shale eagle ford formation. The following challenges were present in this well, **Fig. 16**:

- It was the first unconventional well completed in a shale formation in this region.
- The first stage began with abrasive perforations at 3978 to 4030 m MD (no jetting was performed at that depth).
- Multiple fractures were evenly distributed on a lateral of 1300 m.

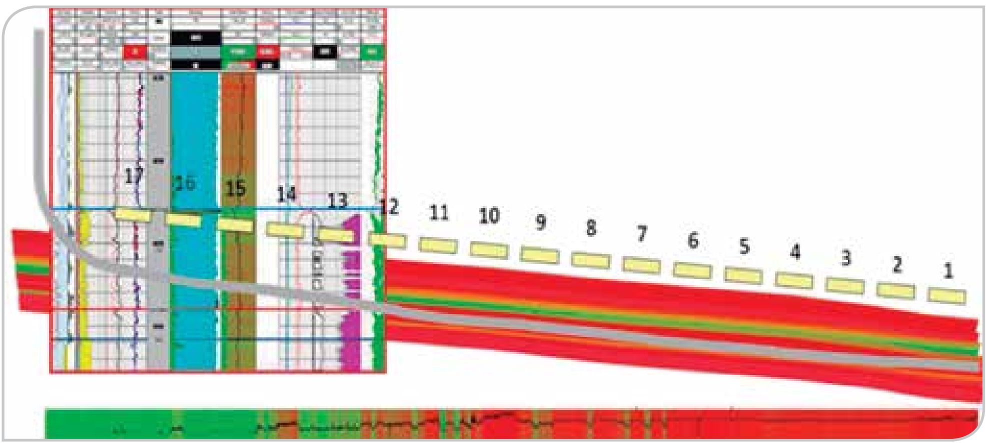

Fig. 16. Case 4 well characteristics.

This well was completed with 5 1/2 in., TRC-85, 23 lb/ft casing at 1787 m and 4 1/2 in., P-110, 15.1 lb/ft casing at 4071 m MD (2539 m TVD) with a lateral section of 1300 m. Formation data were BHP = 5,440 psi, k = 0.0007 md, and θ= 5%. A total of 32 abrasive perforations along the first 16 clusters were performed (3980 to 4030 m Stage 1; 3906 to 3958 m Stage 2; 3834 to 3886 m Stage 3, and 3762 to 3814 m Stage 4; all depths are MD).

Abrasive perforations along the four clusters were planned for the initial stage. Because of changes made to the original design, the first 4 of 17 stages were completed using this technique. However, six cleaning trips were required before beginning the first abrasive perforation.

Fig.17 shows calibration and correlation with a memory GR-CCL log.

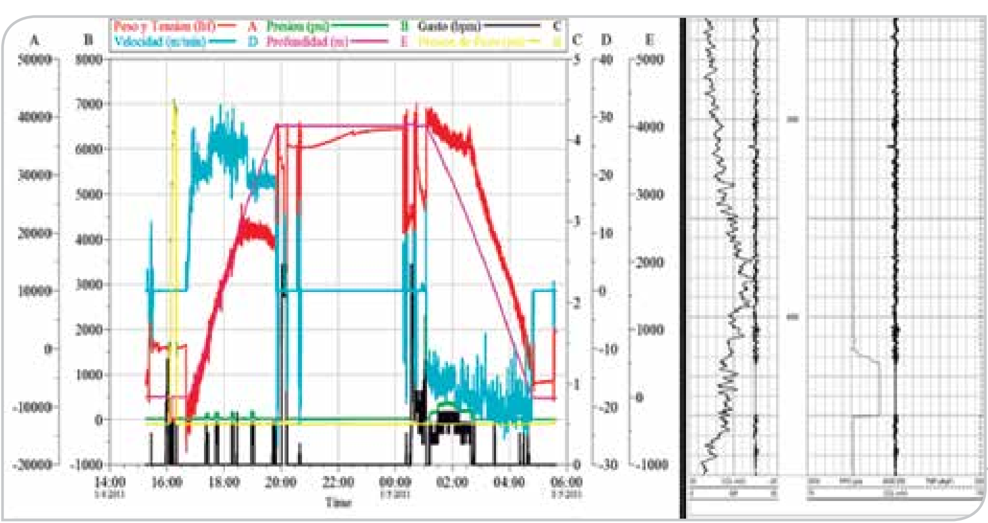

Fig. 17. Calibration and correlation with a memory GR-CCL log.

For this well, 2 in. CT was used with a 3 1/16 in. 60° phase, 6 spf jetting tool. Eight abrasive perforated zones in this zone were performed, which was the first time this technique was used in a shale formation in Mexico (Araujo et al. 2012).

Fig. 18 shows the abrasive perforation along four intervals evenly spaced at 3 m each for the first of the 17 stages.

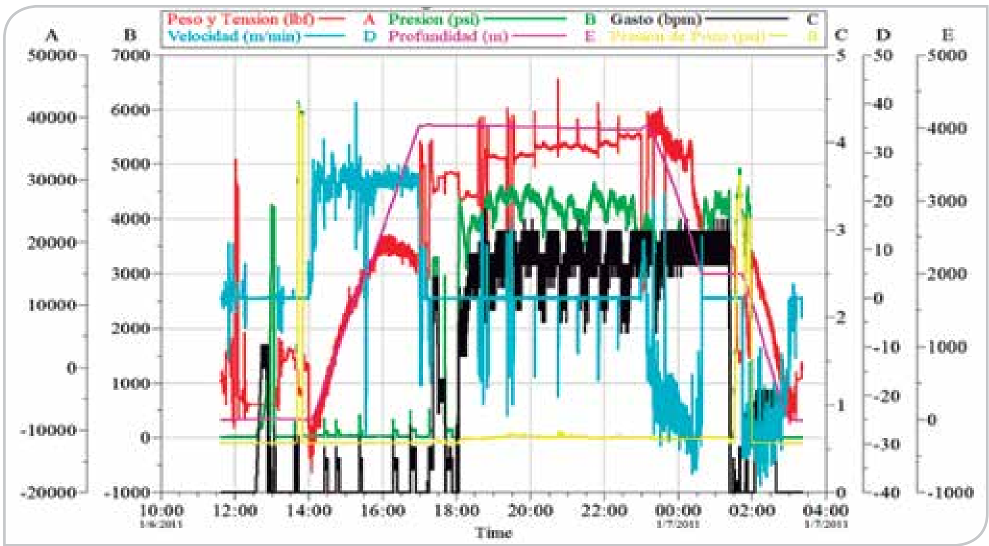

Fig. 18. Abrasive perforating along four intervals.

Fig. 19 shows the multistage hydraulic fracture using slickwater and 250,000 lbm of 40/40- and 70/140-mesh sand on Stage 4.

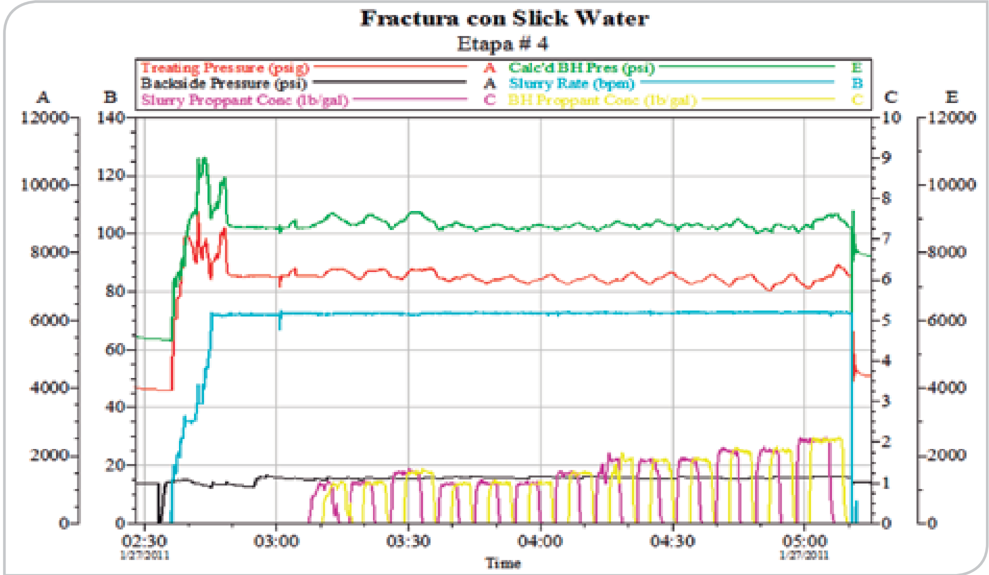

Fig. 19. Stage 4 of 17 stages; hydraulic fracture using slickwater on a HJAF interval.

These four stages with HJAF used 1,004,500 lbm of 70/140- and 40/70-mesh sand, with an average of 250,000 lbm of sand per stage, an average rate of 72 bbl/min, and a maximum concentration of 2.5 lbm/gal sand. 51,000 gal of water were used for these four stages. On all 17 stages, 4.276 million lbm of sand and 181,000 bbl of water were used.

The recorded production of the well was 3.2 MMcfd of gas and a WHP of 2,750 psi.

Case 5: Horizontal Well, Gas-Oil Shale Jurassic Pimienta Formation. This well, **Fig. 20**, presented the following challenges:

- A horizontal well had to be completed only using abrasive perforations and multiple hydraulic fractures because of wellbore problems preventing the use of the perf-and-plug method. This was the first time this technique was performed for an entire lateral in a shale formation in Mexico.

- Multiple fractures were evenly distributed in a lateral of 1500 m, and sand plugs were set in the horizontal section to isolate each treatment.

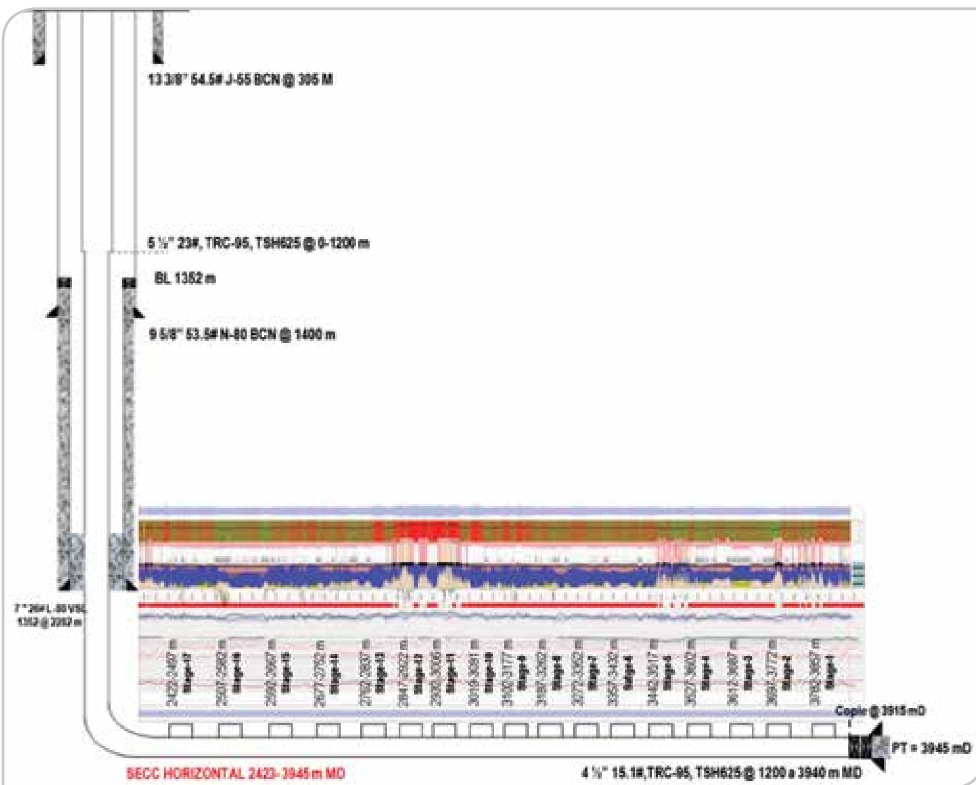

Fig. 20. Case 5 well characteristics.

This well was completed with a 5 1/2 in., TRC-95, TSH625 casing at 1200 m and 4 1/2 in., TRC-95, TSH625 casing at 3945 m MD (2120 m TVD), with a lateral section of 1500 m. Formation parameters were BHP = 4,672 psi, k = 0.00058 md, and θ = 7%. A total of 255 abrasive perforations along 85 clusters using 17 stages were performed on the horizontal section (2422 to 3857 m MD).

This well was initially designed to be completed by perforating five clusters using a hydrajetting tool in the toe of the well and continuing with a perf-and-plug completion method for the next 80 clusters. The completion program was changed because of restrictions encountered in the well that prevented the possibility of setting the plugs at the desired depth. It was decided to complete the entire well using hydraulic fracturing assisted with CT and hydrajetting.

Fig. 21 illustrates Stage 2 using the hydrajetting tool to perforate interval 3697 to 3772 m MD.

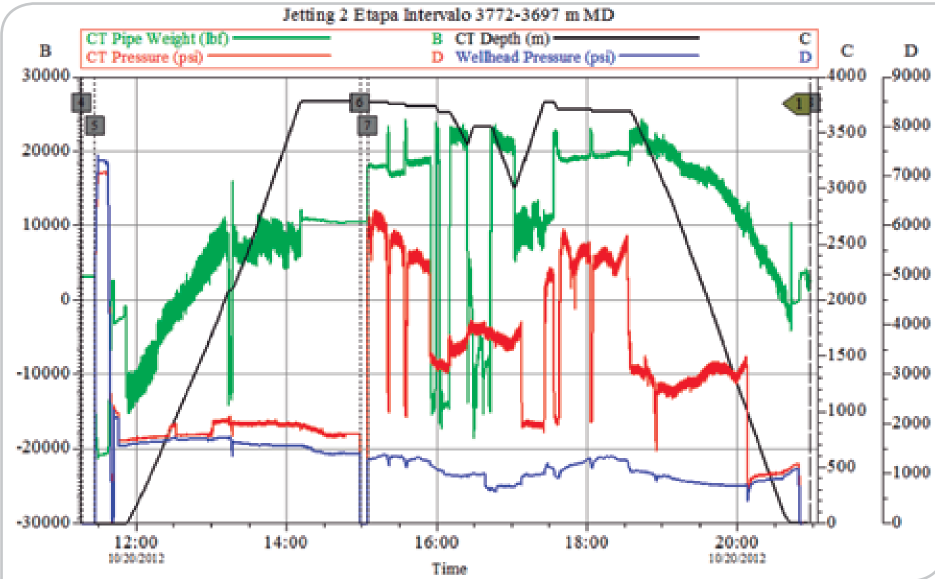

Fig. 21. Stage 2 perforating using the hydrajetting tool.

In this well, 2 in. CT with a 3 1/16 in. hydrajetting tool, 120° phase, was used. A total of nine perforations were made in this zone. This process was then repeated 16 more times to cover the total lateral length. Before each stage, an injection test was pumped to help ensure there was a connection between the wellbore and formation. Before beginning the hydrajetting process, the previous sand plug was tagged and cleaned to the desired depth, circulating the sand excess through the annulus between the wellbore and CT.

Fig. 22 shows one stage of the multistage hydraulic fracturing treatment using a hybrid system (slickwater and crosslinked gel); a total of 150,000 lbm of 70/140- and 40/70-mesh sand and 150,000 lbm of 20/40- and 16/30-mesh curable RCP were pumped.

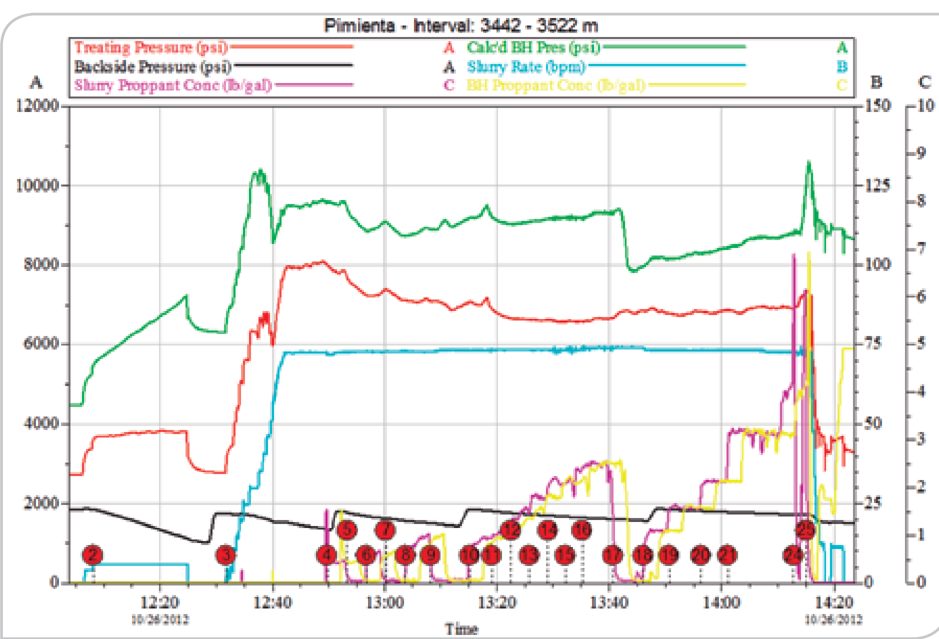

Fig. 22. Multistage hydraulic fracturing treatment using a hybrid system.

For all 17 stages, a total of 2,681,600 lbm of 70/140- and 40/70-mesh sand were pumped and 2,394,800 lbm of 20/40- and 16/30-mesh curable RCP were pumped, yielding an average of 298,630 lbm pumped per stage at 71 bbl/min and a maximum sand concentration of 4 lbm/gal. A total of 5,077 million lbm of proppant and 108,600 bbl of water were used. Average pumping pressure was 6,400 psi. Average production recorded was 250 BOPD (35 API), 1.5 MMscf of gas, and a WHP of 800 psi. Total water recovery reached 30%. This was the first shale oil producer in Mexico. **Table 1.** Provides a summary of the jobs discussed.

Table 1. Summary of Wells performed using HJAF.

Well No.	Interval	Formation	Year	Fracture Stages	Comments
Tight Gas					
1	2120 to 2363 m	PM-10	2011	5	All stages were perforated using hydrajetting. Initial production Qg= 6 MMcfd, WHP= 3,500 psi.
2	1443 to 1780 m	E Yegua Slump	2012	5	All stages were perforated using hydrajetting. Initial production Qg= 1.9 MMcfd, WHP=1,400 psi.
3	1612 to 2076 m	E Yegua Slump	2012	6	All stages were perforated using hydrajetting. Initial production Qg= 13 MMcfd, Qc= 500 BOPD, WHP=2,250 psi.
Shale Gas/Oil					
4	2826 to 4030 m	Eagle Ford	2011	17	First shale performed in Mexico. Four stages were perforated using hydrajetting. Production Qg= 3.2 MMcfd, 2,750 psi WH. Used conventional plug-and-perf technique for next stages.
5	2422 to 3857 m	Jurassic Superior Pimienta	2012	17	First shale light oil producer and was perforated totally with hydrajetting. Initial production Qg= 2.0 MMcfd, Qo= 430 BOPD, 1,300 psi WH.
Other Shale Gas/Oil					
6	1523 to 2077 m	Eagle Ford	2011	16	First stage was perforated using hydrajetting. Used conventional plug-and-perf technique for next stages. Well didn't produce hydrocarbons.
7	2058 to 3656 m	Eagle Ford	2013	16	First stage was perforated using hydrajetting. Used conventional plug-and-perf technique for rest of stages. Initial production Qg= 2.1 MMcfd, Qc= 52 BOPD, 1,250 psi WHP.
8	2711 to 4197 m	Eagle Ford	2013	17	First stage was perforated using hydrajetting. Used conventional plug-and-perf technique for next stages. Initial production Qg= 2.9 MMcfd, Qo= traces, 2,500 psi WHP .

Lessons learned and recommendations

- Well trajectory is fundamental for reducing dogleg severity when running production casing. The use of simulators to check for potential problems when running CT and wireline units can help reduce lost time during completion operations.

- CT cleanup operations before pumping operations are essential in this type of completion. A milling trip replaced the use of a conventional cleaning bottomhole assembly (BHA), to help reduce problems and guarantee the well was clean.

- Mud from the drilling operations should be used to perform compatibility tests with the fluids that will be used during CT operations.

- It is recommended to run a reaming tool before performing hydrajetting tool operations with CT. Doing so helps minimize the risks associated with using CT to reach TD.

- The use of a GR-CCL tool is essential for correlating the exact depth at which perforations are to be made, and also for avoiding the use of hydrajetting in the casing or tubing coupling, which could make it difficult to initiate the fracturing job.

- Pumping injection tests after hydrajetting has proved to be a good practice for connecting the wellbore and formation.

- Pumping an acid spearhead is recommended for reducing any additional friction in the NWB region.

- The use of liquid resin systems (LRS) provides an extra benefit to the fracture; however, it is recommended to avoid this practice when setting the sand plugs, because of possible problems that can occur when cleaning and tagging with CT.

- Sand plug operations in horizontal wells should be pumped as a separate stage in the last sand stage at higher concentrations. They should be tested using significant pressure.

- Recorded data and job simulations are key for making decisions during the completion job.

- For a new job procedure to be implemented, it should be well documented before changing previous job procedures.

- It is very important to be aware that a learning curve exists when performing a new procedure, even if the completion technique was already successfully used in another region.

Conclusions

The following conclusions are a result of this work:

- All of the fracturing stages were pumped and completed as scheduled in these wells. No screenout was observed during the fracturing jobs.

- Hydrajetting perforation is considered to be one of the best options for completing these types of wells, because it helps ensure proper proppant distribution and generates a single fracture, as well as reducing NWB tortuosity.

- Sand plugs, when used as an isolation method, help prevent the need for overflushing of the fracture treatment, which could affect production.

- Sand sweeps, when having high NWB friction at the beginning of each stage, help the fracturing treatment by reducing WHPs.

- The use of LRSs during the last sand stages helps prevent conductivity damage mechanisms, such as proppant diagenesis and regression, which can negatively impact sustaining conductivity over time.

- It is recommended to create alternative pumping schedules. More stages using the same proppant volume reduces pumping rates, and the need for pumping through the annular space between casing and CT. It is important to consider CT pressures and rate limitations when developing these alternative options.

- In all of these jobs, when analyzing each stage, significant amounts of water and additives were saved by reducing the pad stage, increasing sand concentrations, as well as lowering gel concentrations, which resulted in less damage to the formation.

- The use of radioactive and chemical tracers during fracturing stages helped the understanding of how the fracture treatments were injected into formation.

- Microseismic monitoring is recommended in these types of treatments for verifying fracture efficiency and reservoir stimulation, as well as to confirm how pumping rates and the type of fluid used affect fracture geometry.

- Using new alternatives involving pinpoint stimulation is always encouraged, such as CT fracturing assisted with anchors, downhole mixing, etc. This would reduce operation times and required equipment, and would help minimize non-productive time, allowing more fracturing jobs in which proppant is placed precisely, among other benefits.

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