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Successful Drilling of Horizontal Wells in Carbonate Reservoirs with Total Mud Losses

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Abstract

Cantarell is the largest oil field in Mexico located 80 km offshore the coast of Ciudad del Carmen island in the Gulf of Mexico (Fig 1). A horizontal drilling campaign was initiated in 2006 to improve production of the Cantarell field, now in clear declination. This field has a large zone of static total mud losses when drilling the naturally fractured carbonate reservoirs in the Upper, Medium and Lower Cretaceous. Rather than trying to avoid these losses by using under-balance drilling techniques, or preventing them the drilling community has successfully learned to live with them.

Figure 1. Localization of Cantarell in Mexico Golf Coast

The main challenges when drilling with total mud losses are related to the fact that the hydrostatic mud column in the annulus does not reach surface and is not constant, which makes impossible to have full or partial circulation. When mud flow stops, the short mud column generated decreases very fast. Even just lowering the operating flow by 20 gpm can lead to a pressure drop from 1000 psi to close to cero. Basically because the flow has dropped to a level in which the rate of the fluid loss into the fracture is greater than the rate at which fluid is supplied. Once the mud flow resumes, it takes several minutes and a lot of mud to reestablish the hydraulic head.

This situation presents a complex operational challenge directly affecting the drilling performance, steering capability, downhole real-time data transmission, direction and inclination (D&I) surveying, and sending commands to downhole tools (downlinking), as well as hole cleaning and stuck pipe prevention.

Specific solutions were developed by a team effort between the operator company and one of the major drilling services companies in the region. These solutions led to the safe and successful drilling of numerous horizontal wells (building the curve, landing the well and navigating through the lateral section) maintaining complete directional control in this total losses environment with rotary steerable systems and, at the same time, having full real-time communication with downhole tools in the bottomhole assemble (BHA).

Introduction

The typical scenario for drilling a horizontal well in Cantarell field is as follows:

- Total mud losses occur continuously along the landing and horizontal section.
- Formations drilled are the BTPKS Breccia (Tertiary Upper Cretaceous), Middle Cretaceous and Lower Cretaceous; formations with naturally fractured carbonates (limestone and dolomite) for both sections.
- Drilling mud used is polymeric low density water-base mud (WBM) (0.9 g/cc) or sea-water-base mud (1.03 g/cc).

Based on an understanding of the relevant directional drilling aspects of the well and the challenges imposed by the geology, the procedure for drilling these horizontal wells is summarized as follows (Figure 2):

- Build from around 45° to 60° to the landing point at 85° to 90° in 8 ½-in. section with 2.5 to 3.5 deg/100ft of dogleg severity (DLS).
- Maintain tortuosity to a minimum because of completions requirements.
- Navigate laterally in 6 ½-in. or 6 1/8-in. section, although building the curve to the landing point and then continuing drilling horizontally in 6 ½-in. or 6 1/8-in. section has been done as well.

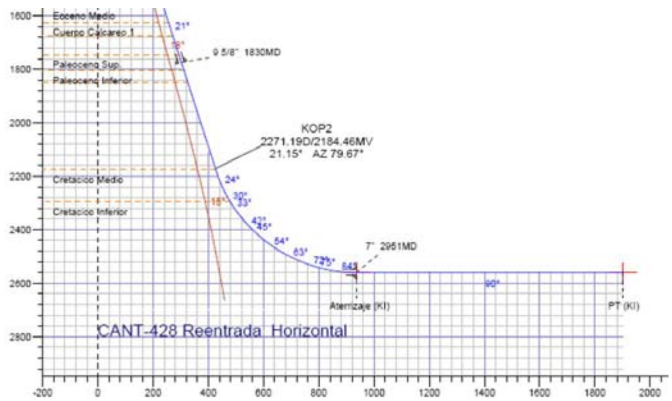

Figure 2. The Cantarell-428 (8 ½-in. and 6 1/8-in. sections) is a typical profile for the field.

Challenges when drilling with total mud losses

The fact that the hydrostatic column does not reach surface and is not constant directly affects hole cleaning, steering capability, downlinking for downhole tools programming, surveying capability, and real-time communication; in the following ways.

Hole Cleaning

A great concern while drilling with total losses is removing cuttings out of the BHA section of the drillstring to prevent stick/slip, steerability problems and stuck pipe incidents.

Steering Capability

Full directional control is a must to land the well properly and avoid tortuosity at the same time. On top of this, the risk of getting stuck without rotation or circulation while sliding eliminates mud motors as a suitable option. Rotary steerable systems (RSS) seem to be the natural answer for this challenge; however, not every RSS will work under total losses. The key of success for a RSS to work under these conditions is that all pieces have to rotate while doing directional work; this is the operating principle of some RSS whether they are push-the-bit or point-the-bit systems.

Downlink and Surveying Capability

The normal procedure of taking directional surveys with the measuring-while-drilling (MWD) tool by cycling the pumps, and sending commands to the RSS by changing the flow rate up and down are practically impossible to perform under total losses conditions. Reducing a small percentage of the flow can dramatically drop the standpipe pressure from 1000 psi to 100 psi, causing the loss of most of the provisional and incomplete hydrostatic column. It might take several minutes to recover the provisional hydrostatic column when bringing up the flow again.

Real-time Communication

Not having a complete hydrostatic column and inconstant stand pipe pressure makes it difficult to demodulate and to keep the MWD signal in synchrony with the surface equipment to avoid loss of real-time data at surface. This problem arises due to the fact that the MWD uses mud pulses to encode and transmit data to sensors installed in the rig stand pipe, in absence of constant and complete mud column inside the drillpipe the mud pulses are not able to table all the way to surface.

Successfully Implemented Solutions

The tools and procedures described in this section have proved to be the main solutions to overcoming all of the challenges described previously:

Auto Survey Mode for MWD Surveying

The auto-survey mode is a time-programmable survey measurement. In this mode, the MWD does not need to cycle the pumps to be shut down to trigger a survey measurement, preventing the loss of the provisional hydrostatic column. Auto-survey mode will simply take and send to surface a survey reading every specified period of time. Since the time of the survey reading is predictable, it is only necessary to stop rotation when the time approaches to get the D&I sensors steady to have a good survey, without shutting down the pumps.

Continuous D&I readings help the directional driller to know the BHA performance before an actual survey is taken, thus allowing for the proper corrections to be made on time. For this to be possible, a reliable MWD signal at surface should be provided which is not usually achieved when total losses occur.

Boosting MWD Signal for Total Losses

The idea behind ensuring a reliable and uninterrupted MWD signal while drilling in the total losses scenario is to keep the drillstring full with mud at all times at constant pressure.

The first approach to achieve this is to use the maximum flow available.

Typical flow rates used in these wells are:

- 390 to 420 gpm for 8 1/2-in. section
- 270 to 290 gpm for 6 1/8-in. section

The next step depends on the type of RSS used. When a point the-bit RSS is used, the best option is to make the bit total flow area (TFA) as low as possible (from 0.147in^2 to 0.186 in^2) since this type of RSS does not have a minimum or a maximum pressure drop requirement below it. With such small TFA at the bit we are creating a big restriction of mud flow and the drillstring will remain full of mud despite the lack of hydrostatic column in the annulus. This allows the MWD tool to stay in synchrony and send a consistent signal to surface.

If drilling with a RSS push-the-bit system, the best method is to select the bit TFA to have the maximum pressure drop allowed by the RSS tool at the highest planned drilling flow rate, this will prevent having the require pressure drop below the minimum limit when the driller reduces the flow rate as normal practice in presence of mud losses. However, this TFA won't generate enough restriction to keep the drillstring full of mud at constant stand pipe pressure, which will result in poor quality of MWD Signal. Therefore the use of an additional flow restriction right above the push-the-bit RSS is needed; this will also facilitate the faster recovery of the mud column inside the drillstring when lowering the flow for the RSS downlinking process.

The RSS tools used in Mexico for this application have been modified to allocate a locally designed device called "Signal Booster" to allow bigger restriction of mud flow without interfering with the tool functionality. This Signal Booster has been also used for RSS Point-the-bit applications where severe mud losses are expected. When this technique has been combined with powerful MWD telemetry systems the result has been a good MWD quality signal with a large amount of LWD data. An example of this is shown in the figure no. 3, where a high quality LWD resistivity image is shown. In this case total mud losses were encountered while drilling highly fractured carbonates at the cretaceous formation, real-time LWD resistivity images were being used to characterize the fractures in order to optimize the completions assembly before reaching the well total depth. A push-the-bit RSS tool with a Signal Booster was used and the real-time log was never interrupted when the total mud loses were detected by a sudden drop in pump pressure from 3200psi to 1394psi.

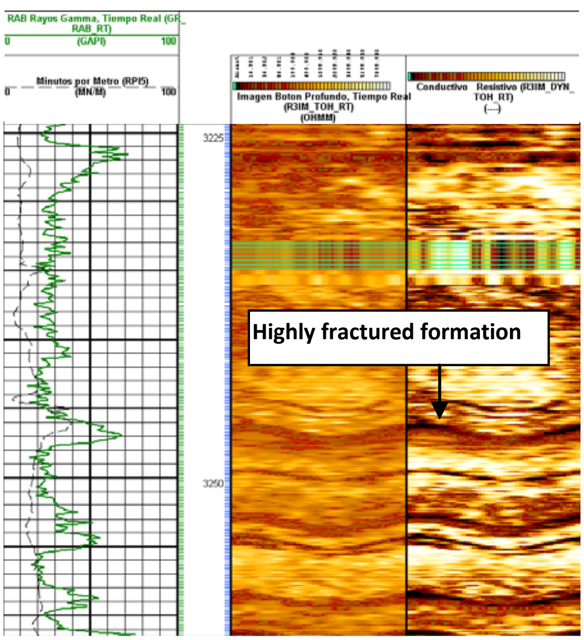

Figure 3. LWD Real-Time resistivity image obtained while drilling through naturally fractured formation under total mud losses conditions.

RSS Down-hole Programming "Downlinking"

The Rotary Steerable Systems control the inclination and direction in which a well is drilled using a steering mechanism that either "pushes" or "points" the bit. The amount and direction of the bit actuation depends on the program stored in the tool electronics. When the program needs to be changed, the DD can send commands to the tool using mainly mud pulse or string rotation. This technique is known as "Downlinking". In mud pulse downlinking, the DD codify the desired command in a series of mud pulses, or downlink sequence, and manually control the flow rate at the driller pumps panel. The RSS recognizes the codes and translates them into a steering instruction and will update the directional control of the trajectory. After accepting the new command, the RSS communicates with the MWD, which sends a signal to surface confirming the reception of the downlink.

Being able to communicate and send commands to the RSS is crucial when building the curve while landing a horizontal well and navigating through the horizontal section. In the total mud losses environment, the downlinking process is not straightforward because of the severe loss of hydrostatic column when lowering the flow rate.

A downlinking telemetry based on flow level recognition is not the most suitable for this scenario, since it will never stay steady while sending the mud pulses as the mud is lost rapidly through the formation. The latest improvement of the RSS tool software called "Fast Downlink" allowed to overcome this problem (Fig 4). The new software uses a pattern of mud flow changes which is mapped to a specific command, rather than a fixed range of mud flow, this allows the tool to better recognize the steering instruction that the directional driller is trying to send. Another big advantage of this software is that the downlinking patter recognizes small variations of flow rate, thus eliminating the loss of the mud column inside the drillstring which at the same time helps to maintain a constant pressure drop across the drillpipe and this helps the RSS software to easily recognize the steering command.

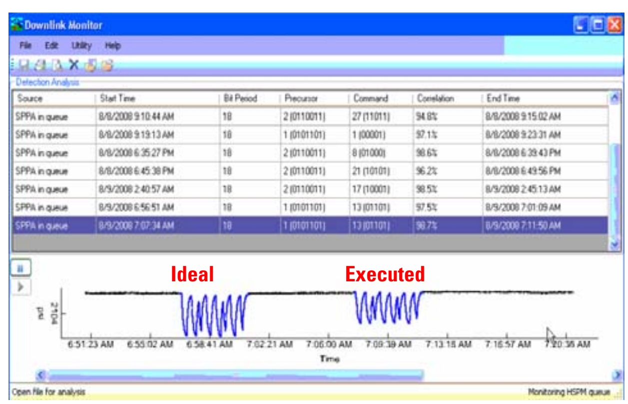

Figure 4. RSS Downlink monitor shows the "Ideal" fluctuation of mud flow that the software expects for the specific steering command aside the "Executed" downlink. Both are similar enough and the software successfully recognizes the steering instruction.

Borehole Cleaning Practices

Borehole cleaning is one of the most complicated operations when drilling horizontal wells with total mud losses. The cuttings can be circulated out of the whole due to the lack of mud returns to surface and they stay somewhere downhole. The only alternative to clean the borehole is by losing as many cuttings as possible into the formation at the same rate that the mud is lost. This task is very complicated since the top level of the mud column in the annulus is not certainly known and big volumes of mud are required based on the severe fractures. Fractures size and density varies from one depth to another so the practices or procedures used in one interval might be not that efficient in a deeper interval.

The obvious ultimate consequence of poor hole cleaning is stuck pipe incidents due to pack off, but there are other problems that arise before this incident happens that affect the drilling performance. The rate of penetration (ROP) dramatically decreases with poor hole cleaning under total mud losses; the typical cuttings bed built in a horizontal well doesn't longer exist in this case due to constant avalanching of cuttings around the BHA. When this happens the BHA is exposed to higher friction and severe torsional vibrations take place, known as the "stick/slip" effect, which is reflected as big variations in torque at surface. High stick/slip not only affects the integrity of the drillstring connections but also affects the orientation capability of the RSS bringing as result the inability of properly steer the well through the plan trajectory, which is critical when landing the well.

Real time well monitoring is critical for the successful execution of this type of wells. Specific downhole measurements for hole cleaning monitoring such as annular pressure while drilling (APWD) usually brings valuable information regarding to solids transport efficiency by the calculation of the equivalent circulating density (ECD), however these measurements become less helpful under total mud losses and horizontal drilling, since the height of mud column in the annulus changes all the time based on the mud losses magnitude. In this case, other indicators such as torque and drag, and downhole shocks and drilling vibrations become the main parameters to monitor and analyze to prevent major drilling incidents due to poor hole cleaning under these circumstances.

After several horizontal wells drilled in this fractured formation specific hole cleaning techniques were developed as best practices that became standard procedures for total mud losses drilling in Mexico. These can be described as follow:

- Mechanical agitation of the drillstring to raise the settled cuttings at the lower side of the wellbore and accumulated around the lower BHA and pushes them away into the loss circulation zone with bigger fractures. This can only be achieved by reaming every joint with full rotation and flow rate and then reaming the stand after finishing drilling in the same way.
- Pumping high-viscosity pills since the mud itself has very low viscosity (Polymeric low density mud or sea water based mud). This helps to carry the cuttings away from the BHA and pushes them into the natural fractures. It has been proven that with an efficient viscous pill procedure the stick/slip is significantly reduced thanks to a better cutting removal (Fig 5), giving as results more constant drilling parameters with higher ROP and good directional control. The high-viscosity pills used have 300 seconds of funnel viscosity and they are pumped every time the stick& slip level indicates cutting accumulation. This can be as frequent as every 5 m drilled and at the end of every stand.

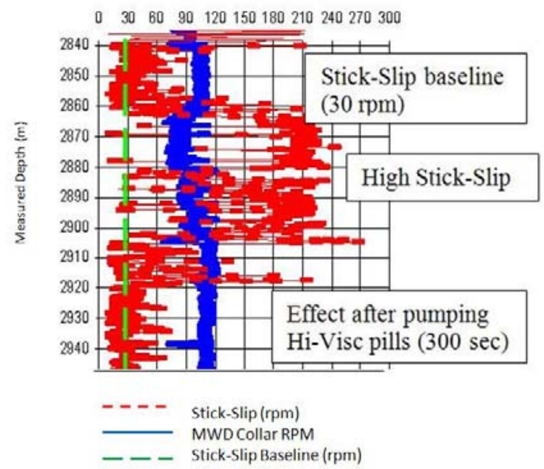

Figure 5. Drilling Mechanics log shows reduction in stick/slip to the baseline levels after pumping a sequence of high viscous pills and removing cuttings from the lower BHA.

- Regular short trips are good indicators of the hole conditions after the hole cleaning procedure of viscous pills and mechanical agitation has been implemented.
- Performing back-reaming more commonly than in normal drilling scenarios. Back-reaming can be done safely by monitoring closely all the drilling mechanics parameters.

Concern of deterioration of mudcake by doing back-reaming will not be an issue in this case because of the loss circulation condition in big natural fractures. These back-reaming trips can be done only if after implementation of previous hole cleaning practices the hole still gives indication of cuttings accumulation also reflected as higher stick&slip levels (Fig. 6). The general recommendations for back reaming in these circumstances are:

- Controlled speed to +/- 300 m/hr maximum, which is the key to avoiding destructive effects on the BHA tools (MWD, LWD and RSS) due to BHA vibrations.
- High RPM (100 to 120 RPM)

- Regular drilling flow rate (390 to 420 gpm for 8 1/2-in. section and 270 to 290 gpm for 6 1/8-in. section)
- Waiting to fill the inside of the drillstring and having a steady standpipe pressure before starting backreaming for each stand.

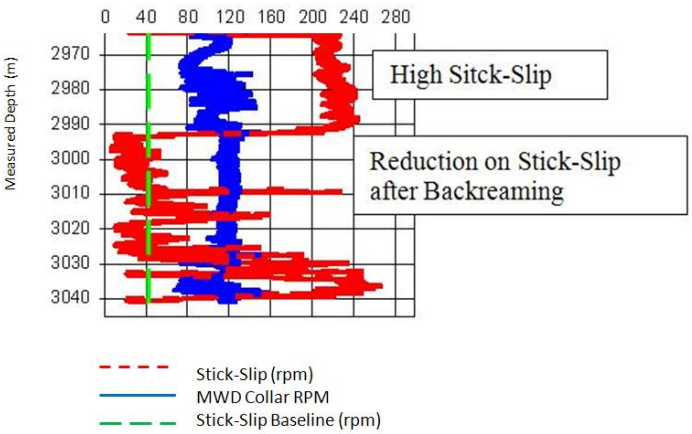

Figure 6. Drilling Mechanics log shows severe stick/slip (200% higher than MWD collar rpm) as indication of poor hole cleaning. Stick/slip is significantly reduced at 2990m after backreaming the stand several times. Stick/slip start increasing again as the bit generate more cuttings incapable of circulate out of the hole.

Optimization of BHA and Drillpipe Design

While the RSS have been identified as the best solution for this type of wells, thanks to its capability to geo-steer with full rotation, they also present some limitation when drilling through big fractures since some of these systems require contact with the formation to reach higher doglegs. The best application in this scenario is the use of a point-the-bit RSS which deflects the bit to the desired direction through a rotating drive shaft that it is independent of the formation contact. This system has been used specifically when high dogleg severities are required to land horizontal wells through fractured formation, giving in these wells build rates of 6 to 7 deg/30m with 80% of its steering capability.

In order to improve the build rate response for push-the-bit RSS, so they can be used when medium dogleg are required, the BHA has been optimized by adding two flex joints (3m length each) right above the RSS tool. With this configuration the lower BHA becomes more flexible and with higher WOB the RSS can reach better build rates. An example of this is shown in the figure no. 7, where is presented the dogleg severities reached in two horizontal offset wells. Both wells were landed with a push-the-bit RSS, but the first one didn't have flexible components as part of the system. Two flex joints were included in the BHA of the second well resulting in much higher and constant build rates.

MD (m)	INCL (°)	BR (°/30m)	TR (°/30m)
2401.83	30.71	-0.30	-0.35
2442.48	34.28	2.63	-2.67
2477.49	36.56	1.95	-1.95
2508.67	39.50	2.83	-0.64
2536.19	41.28	1.94	0.63
2565.92	40.95	-0.33	1.24
2586.87	41.13	0.26	1.83
2607.99	42.13	1.42	2.16
2638.40	43.80	1.65	1.92
2649.68	44.16	0.96	1.65
2673.06	45.83	2.14	3.57

MD (m)	INCL (°)	BR (°/30m)	TR (°/30m)
2400.66	29.34	-1.09	-0.68
2432.33	28.26	-1.02	-0.16
2460.22	26.03	-2.40	-0.80
2489.67	29.57	3.61	-3.40
2517.10	32.41	3.11	-1.99
2542.83	35.75	3.89	-3.70
2573.42	38.93	3.12	0.59
2600.70	43.43	4.95	1.00
2630.01	47.29	3.95	0.68
2658.09	50.31	3.23	0.92
2686.30	53.33	3.21	0.82
2713.94	55.53	2.39	0.30

Figure 7. Left surveys: landing section with push-the-bit RSS without flexible components in the BHA. Right Surveys: landing section through the same formation in a second well with two flex joints as part of the RSS push-the-bit system.

Another important factor to be considered when designing the drillstring for this mud losses conditions is the BHA and drillpipe weight. As mentioned previously the mud column level in the annulus lowers down when entering in total mud loses, thus the weight supported by the top drive is much higher since big part of the drillpipe losses its buoyancy capability. When drilling resumes after every connection and the drillpipe is re-filled with mud the drillstring weight increases even more; the result is a pretty high surface torque to rotate the drillpipe at the required drilling rpm. To counteract this effect the BHAs are designed as light as possible and the drillstring combines 5in 25.6 lbf drillpipe at surface with a long section of 5in 19.5 lbf at the bottom. This configuration has reduced surface torques from 28klbf-ft to 19 klbf-ft when drilling the horizontal section.

Results

The practices described in this paper helped the local oil producer Pemex to carry out successfully a non-conventional horizontal drilling campaign (from 2006 to 2010) aimed increasing the well productivity and increase their cumulative oil production. Over 18 wells were successfully drilled, with horizontal intervals ranging from 120 up to 820 m through the fractured carbonate reservoir with severe/total mud losses (Table 1). None of these wells experienced non productive times due to stuck pipe or lost in hole incidents and all of them were properly landed to the required true vertical depth and drilled through the planned objectives. The two wells with the largest horizontal interval in the campaign were:

- Cantarell-468-V, 820 m in 6 1/8-in. section
- Cantarell-428, 776 m in 6 1/8-in. section

Both wells were successfully drilled with an RSS BHA with MWD and LWD tools, PDC bit, and a severe/total losses scenario.

Well Name	Date	Hole Section	Horizontal Interval	TVD (m)	Mud Type	Weight (gr/cc)
Cant-1009	Oct-06	8 1/2"	184	2,761	Polymeric Low Density	0.91
Cant-3013	May-07	8 1/2"	251	2,585	Polymeric Low Density	0.9
Cant-1070	Jun-07	8 1/2"	116	2,562	Polymeric Low Density	0.9
Cant-3027D	Sep-07	8 1/2"	268	2,760	Polymeric Low Density	0.91
Cant-428	Jun-08	6 1/8"	778	2,560	Polymeric Low Density	0.9
Cant-3062	Mar-08	8 1/2"	118	2,761	Oil Based Mud	0.83
Cant-3062-STV	May-08	8 1/2"	126	2,760	Oil Based Mud	0.83
Cant-3064	Oct-08	6 1/8"	748	2,761	Polymeric Low Density	0.9
Cant-227D	Jan-09	6 1/8"	520	2,579	Polymeric Low Density	0.89
Ek-63	Mar-09	6 1/8"	467	3,120	Polymeric	1.03
Cant-468-STV	Apr-09	6 1/8"	834	2,570	Oil Based Mud	0.89
Balam-65-STV	Jul-09	6 1/8"	471	3,115	Polymeric	1.07
Cant-490H	Jul-09	6 1/8"	305	2,548	Sea Water Based Mud	1.03
Cant-2060H	Jul-09	6 1/8"	461	2,557	Polymeric Low Density	0.89
Cant-470-STV	Oct-09	6 1/8"	250	2,548	Sea Water Based Mud	1.03
Cant-408-STV2	Jan-10	6 1/8"	124	2,545	Sea Water Based Mud	1.03
Cant-3095H	Jan-10	6 1/8"	223	2,900	Low Density Bentonitic	0.91

Table 1. List of wells drilled as part of the non-conventional horizontal drilling campaign in the Cantarell field through a naturally fractured reservoir.

Conclusions

Understanding all the challenges arising from total mud losses helped the drilling operator and the drilling services company to adapt to these conditions and take advantage of the positive points of the environment itself to be successful, as a team, drilling horizontal wells with RSS, running completions smoothly, and ultimately fulfilling their production requirements.

The key elements for success are:

- The use of RSS in which “everything rotates” and no external component remains stationary
- The assurance of a stable column of mud inside the drillstring which allows for a continuous MWD signal and full communication with downhole tools (downhole drilling mechanics parameters and full directional control of the RSS)
- Specific drilling, reaming and backreaming practices in place suitable for the conditions and developed through experience after understanding the environment

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References

1. Hernan Melgares et al. “Remote Automated Directional Drilling” SPE Paper 119761 presented at the IADC Drilling Conference and Exhibition in Amsterdam, 2009.
2. Felipe Gonzalez and Siddhartha Banuet: “Successful Horizontal Well Construction in Naturally Fractured Carbonates Reservoirs”. Presented at the SPE ATW in Merida, Mexico 2008.
3. Siddhartha Banuet: “Advanced Well Geometry Design to Maximize Cantarell Drainage”. Presented at the Mexican Oil Conference and Exhibition in Veracruz, Mexico 2007.