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Integrated Approach to Rotary-Steerable Drilling Optimization Using Concurrent Real-Time Measurement of Near-Bit Borehole Caliper and Near-Bit Vibration

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Abstract

A novel sensor system, integrated into a rotary steerable system (RSS), has led to a new level of drilling optimization by providing the concurrent real-time measurement of near-bit borehole caliper and near-bit vibration. This new sensor system gathers all the information 2 to 3 meters above the drill bit, whereas conventional MWD/LWD sensor measurements are made 20 to 40 meters away from the bit.

Integration of these sensors with an RSS resulted in consistent measurements of borehole caliper and the three principal types of downhole vibration (torsional, lateral, and axial), which has helped facilitate comparative analysis of drill bit and BHA performance for different BHAs and wells. Additionally the real-time drilling data was available to a multi-disciplinary drilling optimization team consisting of engineers and researchers. Remote satellite communication and Internet technologies enabled the team to monitor the downhole drilling conditions around the clock and to provide critical feedback to rig site engineers for minimizing vibration-related failures and for improving drilling efficiencies.

This paper will discuss the application of real-time near-bit caliper and vibration measurements while drilling with various hole-size RSS. One unique feature of this particular RSS is a shop-configurable point-the-bit or push-the-bit mode, depending upon the application. This paper also shows a comparison of borehole conditions and vibration between point-the-bit and push-the-bit modes using an identical RSS, having consistency in stiffness, weight, force applying capability and control system.

Through the integrated sensor and team approach, the ability to detect borehole washout conditions and/or BHA instability due to vibration allows RSS operators to take timely remedial action before the occurrence of downhole RSS failure. As a result, the performance and survivability of the RSS has been remarkably improved.

Introduction

The use of both point-the-bit and push-the-bit RSS has been widely accepted on directional drilling projects. RSS is often used in challenging and complex wells where daily rig rates are very high. The operators have high expectations for RSS performance to reduce drilling days and cut costs. This demand pushes the envelope of RSS reliability by using more aggressive drilling parameters. In order to complete the RSS project successfully, it is crucial to monitor real-time drilling conditions and optimize drilling parameters for increasing the drilling efficiencies and for avoiding vibration-related RSS failures. However, rig-site monitoring of downhole dynamic conditions often has a limited benefit if the information is not shared with multi-disciplinary off-site experts.

As a generation of oil industry professionals matures along with the oil fields, a high percentage of drilling experts will reach retirement age and the industry will lose their expertise in the upcoming years. Knowledge sharing of experienced experts across geographical boundaries will become more important. For example, drilling dynamics knowledge, local field knowledge, and “good old” field experience must work together and overcome upcoming drilling challenges. Real-time near-bit data must be delivered to people with the most expertise with minimum delay. A team of experts in each operating region (e.g. in Houston, Texas, USA) should be able to review the data and contribute to making decisions for real-time drilling optimizations as illustrated in **Figure 1**.

The use of this remote monitoring system reduced the need for required experts at the drilling rigs and increased knowledge sharing among different drilling locations. The system enables the experts to monitor several drilling operations simultaneously and give advice to directional drillers at remote locations. For example, when a decision had to be made using the real-time data, it was common for all team members to participate in discussions from their homes, their office locations, and their travel destinations where Internet connections were available. Even mobile internet terminals or wireless handheld devices (such as BlackBerry®) can be used to monitor real-time drilling conditions as shown in **Figure 2**.

Rotary Steerable System

The particular RSS discussed in this paper can be configured as point-the-bit or push-the-bit, depending on the application as shown in **Figure 3**. Typically the system runs in push-the-bit mode if excessive hole enlargement is expected or higher DLS is required. **Figure 4** shows the 12 1/4"-hole-size RSS in the point-the-bit configuration with its internal and external features. The following section provides a more detailed description of the RSS features.

Non-Rotating Steering Unit

The steering unit of this specific RSS uses three hydraulically actuated pads for directional control. These pads also act as an anti-rotation device, to hold the steering unit stationary while drilling. All three pads make full contact with the formation, and steering is accomplished by offsetting the steering unit in the desired direction. In point-the-bit mode, a full-gauge near-bit stabilizer is used as the fulcrum point, allowing the bit to tilt in the steered direction. In addition to providing a pivoting point, the use of a full-gauge near-bit stabilizer dampens some of the vibrations from the drill bit [1].

The RSS controls the dogleg severity (DLS) by varying the amount of offset that the steering unit creates from the center-line of the hole. The system is designed to maintain Target Toolface and Target Offset in a closed-loop fashion. Typically, the steering unit turns slowly while drilling (1 to 5 revolutions per hour), and the pads are constantly adjusted to achieve the target settings. This continuous adjustment to maintain orientation of the steering unit allows the system to drill a constant curve.

The pads on the steering unit apply a constant force to the borehole wall, essentially acting as hydraulically dampened bushings to stabilize the lower part of the BHA. Variations in hole diameter are accounted for by floating one of the pads, which means that a designated pad hydraulic circuit is open to high pressure fluid from the hydraulic reservoir. This "floating pad" concept allows the tool to maintain sufficient grip, to act as an anti-rotation device, and to provide vibration dampening to the lower part of the BHA for enhanced stability [2].

The RSS is also equipped with electrically controlled hydraulic relief valves in its high-pressure hydraulic reservoir. A downlink command can be transmitted to the RSS to reduce the hydraulic system pressure of the RSS. In certain situations, the RSS is operated in a reduced system pressure mode to increase drilling speed and efficiency.

Integrated Near-bit Sensors

Integration of near-bit sensors with the RSS resulted in consistent measurement of borehole caliper and the three principal types of downhole vibration (torsional, lateral, and axial). In addition, the use of near-bit sensors helped facilitate comparative analysis of drill bit and BHA performance among different BHAs and wells. The sensor system is now a standard, integrated component of all PathFinder rotary steerable tools providing real-time near-bit borehole caliper and vibration severities on all the commercial runs. The advantages of the integrated sensors can be summarized as follows:

- The sensors always measure the near-bit data at the same position in a BHA (either point- or push-the-bit RSS).
- Real-time near-bit data is available for all the RSS runs to improve drilling efficiency.
- The use of integrated sensors does not add extra complexity into the RSS, hence superior reliability.
- The integrated sensors are much more economical and affordable than specialized sensor subs.
- The use of the sensors is transparent to the RSS operator, requiring no extra sensor/battery setups.
- The sensors do not alter the BHA length unlike specialized vibration subs.

Real-Time Pad-Contact Caliper (RPCC)

A unique feature of this particular RSS is a Real-time Pad-Contact Caliper measurement. Since the steering unit uses pad extension to measure offset from the center of the hole, the same measurements are used to calculate accurate hole caliper [2]. Prior to every job, the RSS pad position sensors are fully calibrated and verified in the Repair and Maintenance facility to provide high-quality borehole caliper with an accuracy of $\pm 0.005"$ (in a calibration ring).

Near-bit mechanical caliper measurements while drilling are very useful in determining borehole conditions. It is well known that reduced steering performance and DLS capability are a function of overgauge hole. For instance, maintaining

wellbore quality such as hole gauge is crucial to the steering performance of some RSS. Knowing the actual hole diameter close to the bit not only helps the system maintain accurate constant curvature drilling, but also informs the operator in real time that hole enlargement may be present. Also, the overgauge hole tends to decrease BHA stability and consequently increase lateral vibration. If borehole washout is detected, flow rates and/or drilling speed are adjusted to reduce borehole enlargement.

Each adjustable steering pad can travel up to approximately 1 inch in and out, which makes this RSS more robust in washed-out holes. Other systems having less than 1-inch of pad travel could have a problem in a washed-out hole since the anti-rotation device on the non-rotating housing might rotate with a drillstring.

Real-Time Stick-Slip & Vibration Detection (RSVD)

The vibration problems associated with rotary steerable drilling have been well documented in the past [3,4]. Early detection of potential failure caused by vibration and/or stick-slip is the principal behind the design of this sensor system, which is now a standard component of this RSS.

The near-bit vibration sensor has been integrated into the RSS, featuring detection of the three principal modes of drillstring vibration — torsional, lateral and axial as shown in **Figure 5**. The sensor is located 1.9 meters above the bit in the push-the-bit configuration and 2.8 meters above the bit in the point-the-bit configuration.

To provide this vibration data in real time at surface, the data is categorized by severity levels. Sugiura et al. describes this in more detail in other literature [4]. This data is displayed at the steering screen on the rig floor, MWD unit and the company representative's office and can be sent to remote monitoring centers via satellite and through the internet.

The sensor system provides early warning of unwanted vibration and stick-slip that could potentially cause failure of BHA components, MWD/LWD and/or the RSS. When high levels of vibration and/or stick-slip are detected, the Directional Driller can change surface parameters in an attempt to reduce vibration and/or stick-slip to acceptable levels.

Downhole Problems Detected with the RSS

PathFinder has conducted a series of extensive field tests with the various hole-size rotary steerable systems (RSS) since 2004. The RSS, incorporating the RPCC and RSVD features, detected various problematic downhole conditions. This section shows some of the most commonly observed borehole problems and harmful vibration cases. When a downhole failure occurred, caliper and vibration information stored in memory was used for more detailed post-run analysis, the root cause of the failure was investigated, and the failed component was redesigned for more durability.

Washed-out Borehole

The 12 ¼"-hole-size push-the-bit RSS was used in East Texas. A real-time depth-based log in **Figure 6** shows a typical borehole washout up to 13.5" in a soft unconsolidated formation from X650ft to X800ft. The near-bit mechanical caliper (CALI3D) became more than 13.5" while MWD gamma (GRC AAPI) in Track 1 read low and ROP in Track 3 became high up to 180 ft/hr. This real-time data section shows the correlation among the formation softness, near-bit caliper reading, and increased ROP. The push-the-bit RSS maintained control in these challenging borehole conditions with Toolface = 70°L (70 degrees left) and 40% offset setting (Offset = 0.14") as shown in Track 2 and successfully achieved a compound build and turn at low inclination (1°~2°).

While drilling in washed-out hole, the MWD and RSS vibrations were minimal. The MWD vibration data was measured approximately 50 feet above the bit, providing the number of lateral vibration counts above 20 G per second. The MWD lateral vibration count (VIBRATION COUNTS CPS) was between 0 and 10 CPS shown in red in Track 3. There were no signs of torsional, lateral and axial vibration (SS3D, VIBXY3D, and VIBZ3D respectively in **Figure 6**) problems at the RSS, indicating that the rotary steerable BHA was stable in washed-out hole.

Borehole Spiral

A spiraled hole is commonly observed with many drilling assemblies, depending upon a bit type, BHA tendency and formation [5, 6, 7]. When borehole spiraling occurs, the evidence can be found in wireline logs and LWD logs. For example, a resistivity log might show periodic peaks in sensor readings or, more directly, caliper (imaging) tools can detect spiral holes. **Figure 7** shows an example of borehole spiraling in Tracks 1 and 2 observed in an azimuthal caliper image. A conventional motor assembly rotated from X470ft to X508ft MD and from X527ft to X555ft MD. The 2-to-3-foot "pitch" can be observed in a blue circled area from X490ft to X500ft MD. Azimuthal data was not acquired while sliding from X508ft to X527ft MD.

Typically, when the RSS steering unit rotates slowly (e.g. one revolution per hour), the extension of the pads are adjusted accordingly to maintain the programmed toolface and offset, resulting in a sinusoidal adjustment of the pad position,

provided that a borehole size is consistent. In this case, the frequency of the pad extension change may be related to the frequency of the housing roll speed (or steering unit roll speed). When the pads go through a spiraled hole, the adjustment of the pad position may be much faster than the housing rolling speed, depending on the spiral frequency.

At the Rocky Mountain Oilfield Testing Center (RMOTC) in Wyoming, USA, a bit test was run with a 12 1/4"-hole-size push-the-bit RSS to compare performance of two types of drill bits: a milled tooth bit and a tapered-gauge PDC bit. Two drill bits drilled in the same formation (Steele) with the same deflection (offset) rate and similar surface parameters (WOB = 10 ~ 20 klbs, Rotary Speed = 100 RPM, and Flow rate = 720 ~ 750 GPM).

First, a general-purpose milled tooth bit was used to assess maximum DLS with a push-the-bit RSS. **Figure 8** shows the sections drilled with the milled tooth bit. The memory data set shows that actual toolface (ATF3D) and offset (AOS3D), as well as near-bit inclination (INC3D) are all rapidly oscillating, which indicates a suspected borehole spiraling. Also, the steering housing (B1TF3D) rotated non-uniformly. The borehole caliper was erratic with an average borehole size of 12.5" (1/4" overgauge). The resultant average DLS was 4.2°/100ft. The MWD tool detected high lateral vibration counts in real time. The MWD lateral vibration count (VIBRATION COUNTS CPS) was approximately 200 on average. The lateral and axial vibration levels at the RSS were 6 and 3 respectively. In summary, the near-bit data shows that bit and BHA were highly unstable.

In the following bit test run, the suspected hole spiraling was eliminated using a rotary-steerable PDC bit. **Figure 9** shows the sections drilled with the tapered gauge PDC bit matched with this particular RSS. The memory data set shows that actual toolface (ATF3D) and offset (AOS3D) as well as near-bit inclination (INC3D), are all steady and smooth. Also, the steering housing (B1TF3D) rotated smoothly at uniform rotation speed. The borehole caliper was consistent with an average borehole size of 12.27" indicating a high-quality borehole. The push-the-bit RSS with a tapered-gauge PDC drilled a smooth borehole indicating no signs of hole spiraling. The resultant average DLS was 5.8°/100ft. The MWD lateral vibration count (VIBRATION COUNTS CPS) was 0. The lateral and axial vibration levels at RSS were 2 and 1 respectively. There were no signs of torsional, lateral or axial vibration (SS3D, VIBXY3D, or VIBZ3D respectively in **Figure 9**) problems at the RSS. The bit and BHA instability was eliminated with the rotary-steerable PDC bits.

Full-Stall Stick-Slip

Figures 10 and 11 illustrate full-blown stick-slip observed on a rig in the Gulf of Mexico while drilling in a "ratty" abrasive sandstone section with the 8 1/2"-hole-size RSS. Post-drilling LWD data analysis showed that this section consisted of interbedded siltstone, shale, and sand. Very slow drilling (low ROP) and high/erratic string torque between 10 to 25K ft-lb were encountered.

Figure 10 shows surface parameters/data during downhole full-blown stick-slip. **Figure 11** shows downhole-computed mean and raw RPM vs. blade housing (steering unit) toolface angle. It is noticed that rotary torque correlated highly with the downhole stick-slip data while the WOB was kept nearly constant. The Set_RPM is the programmed surface RPM that is different from the actual surface RPM (not shown).

In **Figure 11**, the slowly changing BL1_TF (blade housing toolface angle between 140° and 170°) indicates that the non-rotating blade housing was substantially stationary as compared with the drillstring rotation (about 120 RPM). During the stick-slip period, the maximum raw RPM (240 ~ 360 RPM) was 2 or 3 times higher than the surface RPM (≈ 120 RPM). The corresponding Stick-slip Severity (SS%) in the period is between 200% and 300%.

PDC and Rock Bit Comparison

The GTI Test Facility in Catoosa, Oklahoma, USA was used to evaluate the prototype 8 1/2"-hole-size RSS for performance, ruggedness and reliability. **Figure 12** shows real-time MWD and RSS vibration data collected at the GTI facility, including the surface parameters. The MWD vibration data was measured approximately 45 feet above the bit, providing the number of vibration counts above 20 G per second.

Vibration profiles between PDC and roller cone bits were compared using the RSVD system. The PDC bit induced more lateral vibrations, whereas the rock bit produced more axial vibrations. The real-time vibration data (Lateral Vibration = Low and Axial Vibration = Low) obtained with the RSVD system at the RSS correlated highly with the vibration counts (≈ 100 counts/second ... considered as a low vibration count) detected at the conventional MWD tool. While drilling through a hard dolomite section, called the Arbuckle group (not shown), this BHA suffered from high vibration counts (≈ 450 counts/second) and high near-bit lateral vibration at the RSS. This vibration problem eventually resulted in RSS failure.

Excessive Vibration from Dull Insert Bit

The 8 1/2"-hole-size point-the-bit RSS was used on the drop section (2°/100ft) of an S-shape well. An insert bit was chosen for this particular application due to concerns over bit balling. **Figure 13** shows a brand new bit before the run. **Figure 14**

shows the sections drilled with the insert bit. The MWD and RSS vibration increased without obvious formation changes. The MWD lateral vibration count (VIBRATION COUNTS CPS) became approximately 200 CPS on average. The real-time lateral (VIBXY3D) and axial vibration (VIBZ3D) levels at the RSS became 1 and 2 respectively. A real-time near-bit caliper increase from 8 1/2" to 8 3/4" was observed. The RSS was pulled out due to vibration and consequent low ROP issues. On the surface, the bit was more than 1" undergauge as shown in **Figures 15 and 16**. The Real-Time Stick-Slip & Vibration Detection (RSVD) provided the RSS operator with an early alert of the bit and BHA instability due to bit wear and resulted in timely trip-out of the BHA before the vibration caused a BHA component failure.

Point-the-Bit and Push-the-bit Comparison

The Rocky Mountain Oilfield Testing Center (RMOTC) was used to evaluate an 8 1/2"-hole-size point- and push-the-bit RSS. A commercial point-the-bit and a prototype push-the-bit tools were used to assess the maximum build rate. Prior to this test, contact-point spacing and sizes, bit and other BHA components were optimized for the maximum stability, steerability, and directional capability. The two different BHAs drilled in the same formation (Steele) with similar deflection (offset) rates and surface parameters (WOB = 10 ~ 12 klbs, Rotary Speed = 100 RPM, and Flow rate = 400 ~ 440 GPM). In this test, concurrent near-bit caliper and vibration data enabled the engineers and researchers to make a comparative analysis of bit and BHA stability and borehole quality between two distinct RSS configurations.

Figures 17 and 18 show the memory data retrieved from the two assemblies. Both RSS BHAs exhibited similar drillability (good ROP), stability (good lateral and axial stability) and borehole quality (consistent gauged borehole) as shown in **Table 1**. The only notable difference between the two is the average build rate. The build rate with a point-the-bit configuration was 10.0°/100ft while the push-the-bit configuration produced 11.4°/100ft. More detailed test results are described by Jones et al. in other literature [8].

Real-time Drilling Optimization

This particular RSS is the industry's only system that provides concurrent measurement of real-time near-bit caliper and vibration with integrated sensors. The real-time data has helped to better understand complex downhole dynamics and to mitigate for undesirable downhole conditions and failures in challenging drilling conditions. For example, this real-time measurement has been successfully used for RSS runs with simultaneous hole enlargement [9]. Comprehensive real-time vibration and caliper data was delivered in real time to a multi-disciplinary drilling optimization team consisting of engineers and researchers through a secure web-based real-time monitoring and data delivery system. The system was used to share experts' knowledge with drilling operation personnel.

Well Results

Throughout 2006 and 2007, real-time RSS optimization has successfully been used to drill directional wells worldwide both onshore and offshore. In this section, three example wells illustrate the directional drilling optimization and cost savings associated with this RSS using near-bit caliper and vibration information.

Well A - "S" Type Well in Louisiana, USA – Shallow Kick-Off

This S-shape well was drilled in 2006 from an inland barge in Louisiana, USA. The 12 1/4" section of the well was planned with a 5000ft kickoff point (KOP) to build at 2°/100ft to 20° inclination, maintain for 2000ft then drop back to vertical at 1.5°/100ft to intersect the target. The formations in this area are renowned for being very soft and are typically drilled with water-based mud (WBM). There was concern regarding borehole washout and the consequent loss of directional control from the RSS. Another concern was bit balling in the sticky clays so the bit had to be nozzled with sufficient Hydraulic Horsepower (HSI) to clean the bit. The push-the-bit RSS was selected for the application due to its known ability to operate in overgauge hole and cope with certain levels of BHA and bit balling without affecting the directional control.

A milled tooth bit was chosen for this particular application. Due to concerns over borehole washout and bit balling, the total flow area (TFA) was carefully selected to be optimized for both scenarios. The bit was dressed to provide a 0.74 TFA, which resulted in 1.8 HSI at 600 GPM and 3.72 HSI at 750 GPM. This arrangement provided a good flow operating band to cover any potential washout or balling problems that might occur throughout the run. Mini-extended nozzles were also selected to minimize the amount of washout that is typically seen with standard nozzles on a rock bit. The bit hydraulic optimization was one of the most critical factors in this RSS application.

The 12 1/4" BHA was tripped in the hole at 4000ft and drilled out the shoe track and shoe. With 1000ft to drill before the planned KOP, it was decided to attempt to nudge the well to build angle slightly and turn onto the proposed azimuth. This practice allowed the well to get ahead on vertical section just in case directional problems were encountered deeper down. Since the formations were softer at this shallower depth, it was a good test for the controllability of the push-the-bit RSS.

The well already had 1.5° inclination heading on a 50° azimuth. The tool was set on a 40% offset setting and by using toolface sets between 30°L and 90°L, the angle was built to 4.5° inclination and azimuth turned due North. The caliper was

very erratic varying from 12.3" to 13.0" but the tool managed to produce the required build and turn averaging 1.0°/100ft DLS. **Figure 19** shows a log of the RSS memory data highlighting the caliper measurement and on-bottom downlink programming. The patented non-intrusive RPM downlink on the fly enabled the RSS operator to make minor steering adjustments while drilling ahead [10,11,12].

Because the kick-off started earlier than expected, the pads on the RSS tool were collapsed. The assembly was drilled ahead to assess the behavior of the BHA. The assembly drilled 1000ft maintaining 4.5° inclination; however, the azimuth walked 9° to the right, which was not surprising with such a low inclination.

At 5340ft the tool was downlinked into steer mode on 20°L (20° left) toolface and 30% offset to continue building the curve and turn the well back to the left. When the azimuth was aligned, the TF was set high-side to continue the build to tangent angle. Once again erratic overgauge hole was present during the build section but the push-the-bit RSS continued to build at 1.5°-2.0°/100ft. This was accomplished by optimizing the flow rate, based on real-time near-bit caliper feedback. By increasing the flow rate, when possible, the chance of bit balling was reduced. **Figure 20** shows RSS inclination and caliper measurements from tool memory during the build section.

The tangent section of the well was drilled using a combination of manual steering and automated inclination control. **Figure 21** shows that once again the hole was overgauge and erratic. The flow rate was varied between 650 and 750 GPM to optimize directional control when passing between sand and shale sequences. **Figure 22** shows vibration memory data in overgauge hole from this tangent section. Lateral vibration (VibXY in pink) and axial vibration (VibZ in green) both increased in an overgauge borehole. This data set shows that erratic holes (rapid changes in hole diameter) and overgauge holes increase not only lateral vibration but also axial vibration near the drill bit. This plot indicates that the steering unit stabilized the BHA not only laterally but also axially when all three pads made full contact with the formation. **Figure 23** shows a corresponding real-time caliper and vibration log from the section. It was observed in real time that lateral and axial vibration (VibXY and VibZ) increased in overgauge borehole sections.

The drop section was controlled in a similar manner by using the real-time caliper measurement for feedback to adjust the flow rate and other surface parameters when required to keep the drop rates consistent and predictable. **Figure 24** shows the RSS BHA when POOH at section TD. The image shows that the clays were extremely sticky.

The use of real-time satellite information allowed the RSS technical advisors to monitor the job from home or mobile device and feedback comments through a web-based communication system. This system allowed the knowledge being gained on this particular well to be shared with other regions globally to ensure future success in similar environments.

Well B – “S” Type Well in North Texas, USA - Shallow Kick-Off

This well was drilled in 2006 from a land rig in North Texas. With the 13 3/8" casing set at 400ft, the 12 1/4" section was planned with a shallow 800ft KOP. The plan was to build at 2°/100ft to 18° inclination, maintain for 2200ft and drop back to vertical at 2°/100ft by 9 5/8" casing point at 4600ft. The formations in the area are known to be interbedded with very soft sections so borehole wash-out was a concern. The use of WBM meant that the bit hydraulics had to be optimized to make the most of the available flow. The push-the-bit RSS was selected for this application due to its known ability to operate in overgauge hole and cope with certain levels of BHA and bit balling without affecting the directional control.

A PDC bit was selected for this application so that the section could be drilled in one run with good penetration rates. A 5-bladed 19mm cutter size design with 3" gauge pad length was used. The bit was dressed with 0.981 TFA to give a good operating flow rate band. For some RSS, it is recommended to open nozzles as much as possible just to avoid borehole washout and consequent loss of directional control. However, the disadvantage could be the time wasted cleaning balled bits and, in the worst case, pumping sweeps and pills. The bit hydraulic optimization mentioned above allowed the Directional Driller to control the flow rate, based on the real-time caliper measurements.

The real-time caliper feedback indicated that severe hole washout was present as the caliper was reading a maximum of 13 1/2". The flow rate was varied between 450 GPM and 670 GPM throughout the section to ensure consistent directional control from the RSS. The section was drilled to plan maintaining all directional objectives.

Figure 25 shows a section of data where hole enlargement was present. The purple line in the left track indicates Pad-Contact Caliper measurements (CALI3D). As can be seen, the caliper was reading between 12.5" and 13.5". The blue line in the left track (RPM3D) indicates downhole RPM. A hydraulic system pressure command was given while drilling ahead. This command set the tool to reduce the hydraulic operating pressure to 60% of maximum and helped prevent the pads from pushing into the soft unconsolidated formation. The green line in the left track (HPR3D) indicates the hydraulic system pressure. When the downlink command was accepted, the RSS operator was able to confirm in real time that the hydraulic

pressure reduced from 100% to 60%. A combination of hydraulic system pressure reduction and flow rate reduction to 470 GPM allowed the borehole caliper (CALI3D) to be reduced to 12.5”.

Figure 26 represents the real-time log. The green curve in the left track shows the real-time caliper measurement (CALI3D). It can be seen that the caliper is varying between 12.5” and 13.5”. Even with such a variation in hole size, the RSS still manages to maintain inclination at 16.7°.

As an experiment, the assembly drilled ahead with the RSS pads retracted (no steering) to assess the directional response. **Figure 27** shows the RSS pads were retracted. The assembly maintained inclination well partly due to the fact that it had been designed as a very neutral assembly when the RSS applied no steering force.

Overall the push-the-bit RSS assembly performed exceptionally well in challenging hole conditions. Once again the use of real-time satellite information allowed the RSS technical advisors to monitor the job from home or mobile device and feedback comments using a web-based communication system.

Well C – “J” Type well in UK Sector Southern North Sea

This well was drilled in 2007 in the UK sector of the Southern North Sea. The 12 ¼” point-the-bit RSS assembly was selected for this application through the Zechstein (Permian) using salt-saturated WBM. Although some formations in the area are known to wash out, previous experience indicated that the wellplan could be designed and planned to optimize operational parameters around these problematic formations. The wellplan called to drill vertical from 2300m to 2600m, kick off and build at 3°/100ft to 24° inclination and maintain to casing point. The well was designed to maintain vertical through the Leine Potash which is known for excessive washout from previous offset wells.

A 6-bladed 16mm PDC bit with 3” gauge length was selected. The RSS was set up to maintain verticality. Drilling commenced through the Zechstein sequence with the RSS maintaining inclination below 1°. As expected, as soon as the Leine Potash was drilled, the caliper reading increased to above 13”. The flowrate was reduced from 1000 GPM to 800 GPM to keep the steering unit pads in contact with the borehole wall and attempt to limit the lateral vibration. **Figure 28** shows caliper data in the Leine Potash. It is clear that the hole has been severely washed-out even at lower flowrates. The pad reach on this particular RSS was sufficient to maintain the non-rotating steering unit in contact and prevent housing slip and excess vibration. As soon as the Leine Halite was encountered at 12:20 hrs shown in **Figure 28**, the caliper reduced to 12.25” and began to “flat-line”, indicating very good borehole quality. Gauge borehole reduced not only lateral vibration but also axial vibration near the bit.

Figure 29 shows a plot of caliper and vibration data in the transition from Leine Potash to Leine Halite. As the Leine Halite was encountered at 12:20 hrs, the near-bit caliper (Caliper in blue) reduced to 12.25” on gauge. Lateral vibration (VibXY in pink) and axial vibration (VibZ in green) were both reduced in the Leine Halite.

Once in the Halite, the kick-off was initiated and the well was turned onto a 200° azimuth. 43% offset produced consistent 3° DLS as shown in **Table 2**. The consistency in the DLS was a direct result of the quality of the wellbore as was seen from the caliper “straight-lining”.

Overall the point-the-bit RSS performed exceptionally well through these formations. The use of real-time caliper and vibration feedback helped take proper remedial actions against problematic downhole conditions and thus ensured directional success. The use of real-time caliper data has proven to be very advantageous when drilling the challenging formations found in the Southern North Sea.

Conclusion

- Concurrent measurement of near-bit caliper and vibration revealed that erratic holes (rapid changes in hole diameter) and overgauge holes increase not only lateral vibration but also axial vibration.
- The steering unit of this particular RSS advantageously stabilizes the BHA not only laterally but also axially when all three pads make full contact with the formation.
- Bit hydraulic optimization is necessary to avoid borehole erosion and bit balling in soft, unconsolidated formations.

- The real-time caliper, along with optimized bit hydraulics, helps RSS operators to minimize a chance of borehole washout, thus to produce gauged, quality borehole and predictable RSS response.
- The Real-time Stick-slip and Vibration Detection system, integrated into the particular RSS, is a cost-effective near-bit vibration sensor, which is now a standard component of all tools. The sensor system was effective for detecting various downhole dynamic conditions in real time.
- The real-time near-bit stick-slip and vibration data, along with near-bit caliper measurements, is always available to Directional Drillers and MWD Engineers while drilling complex 3D wells using an RSS. The sensor system leads to optimized drilling parameters in most of the RSS runs by avoiding under-utilization of the near-bit sensor information.
- The use of a remote monitoring system enables experts' knowledge and experience to be shared across geographical boundaries.

Acknowledgments

The authors would like to thank different operating companies for their willingness to publish this data obtained with the 8 ½"- to 12 ¼"-hole-size PathMaker® RSS. We are grateful to PathFinder Energy Services for permitting the publication of this work.

Nomenclature

<i>BHA</i>	=	<i>Bottom Hole Assembly</i>
<i>CPS</i>	=	<i>Counts Per Second</i>
<i>DLS</i>	=	<i>Dogleg Severity (degrees per 100 feet)</i>
<i>GPM</i>	=	<i>Gallons Per Minute</i>
<i>HOG</i>	=	<i>Hole On Gauge</i>
<i>HSI</i>	=	<i>Hydraulic Horsepower per Square Inch</i>
<i>KOP</i>	=	<i>KickOff Point</i>
<i>LWD</i>	=	<i>Logging While Drilling</i>
<i>MD</i>	=	<i>Measured Depth</i>
<i>MWD</i>	=	<i>Measurement While Drilling</i>
<i>NB</i>	=	<i>Near Bit</i>
<i>PDC</i>	=	<i>Polycrystalline Diamond Compact</i>
<i>POOH</i>	=	<i>Pull Out of Hole</i>
<i>ROP</i>	=	<i>Drilling Rate Of Penetration</i>
<i>RPM</i>	=	<i>Revolutions Per Minute</i>
<i>RSS</i>	=	<i>Rotary Steerable System</i>
<i>RSVD</i>	=	<i>Real-time Stick-slip and Vibration Detection</i>
<i>SS%</i>	=	<i>Stick-slip Severity in Percentage ($\Delta\text{RPM} / \text{Mean_RPM} * 100\%$)</i>
<i>TD</i>	=	<i>Target Depth</i>
<i>TFA</i>	=	<i>Total Flow Area</i>
<i>TVD</i>	=	<i>True Vertical Depth</i>
<i>VS</i>	=	<i>Vertical Section</i>
<i>WBM</i>	=	<i>Water-Based Mud</i>
<i>WOB</i>	=	<i>Weight On Bit</i>

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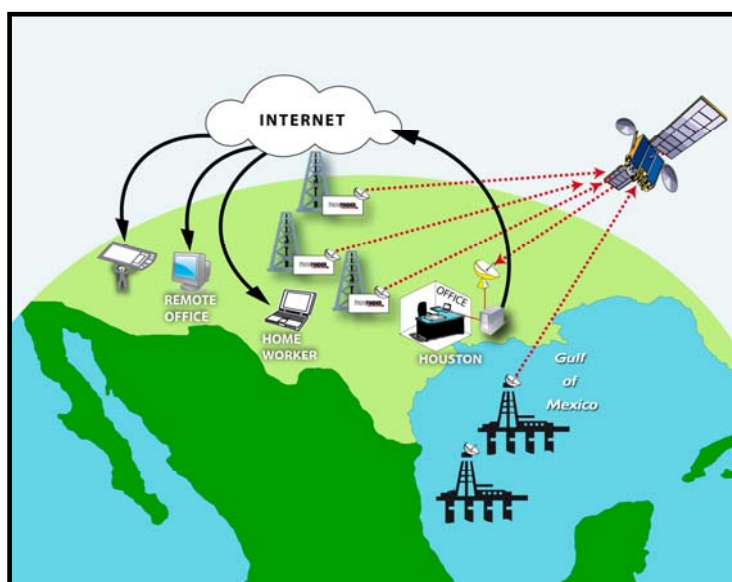


Figure 1: Real-time near-bit data is delivered to a team of experts in each operating region (e.g. in Houston, Texas, USA) and/or any other locations across geographical boundaries.

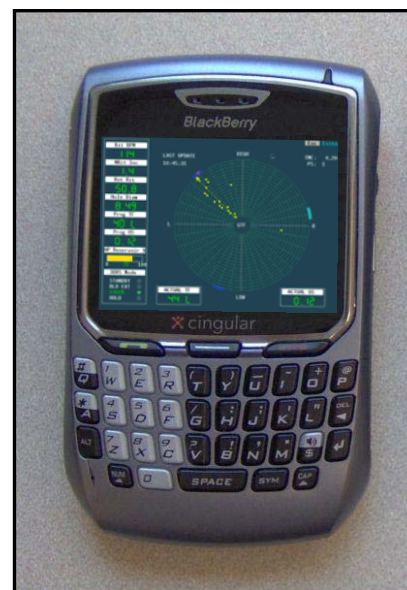


Figure 2: Wireless handheld devices (e.g. BlackBerry®) are used to monitor real-time drilling conditions.

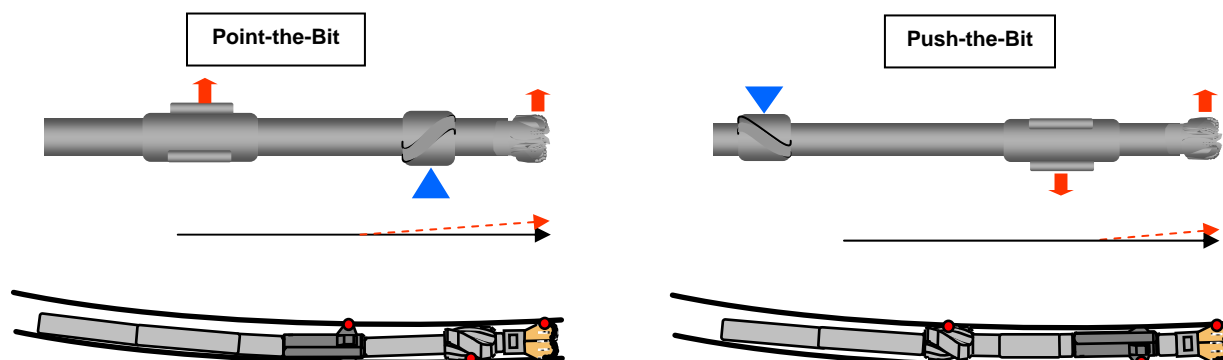


Figure 3: The particular RSS discussed in this paper can be configured as a point-the-bit or push-the-bit, depending on the application.

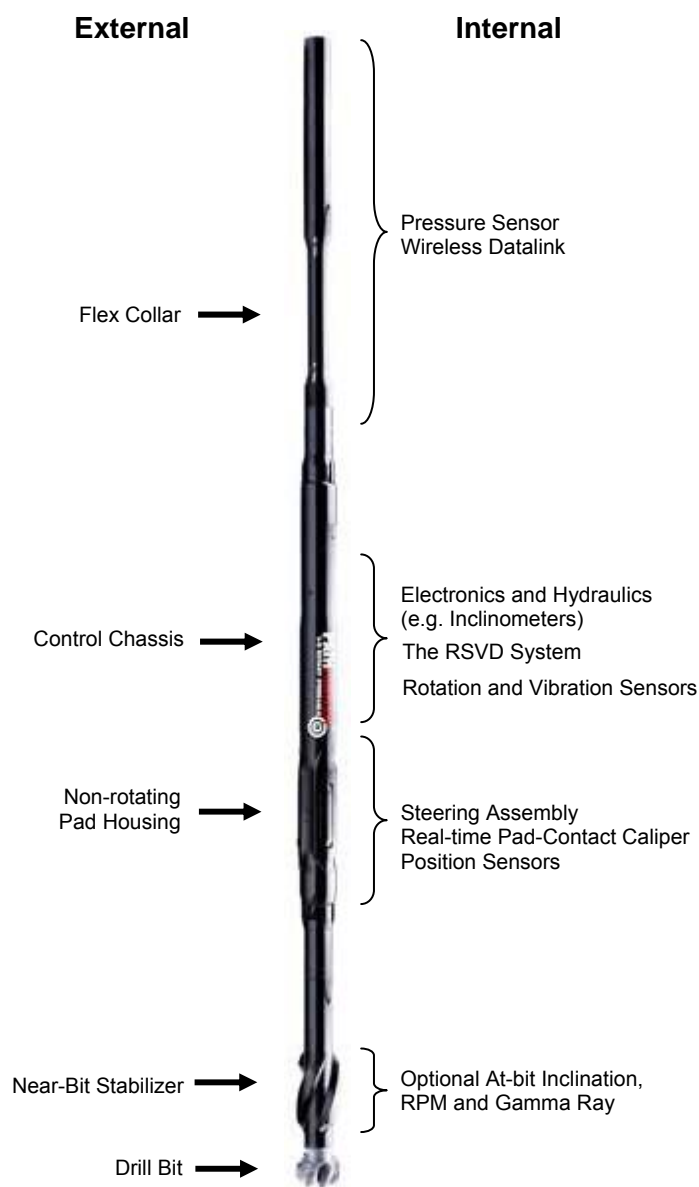


Figure 4: The 12 1/4-inch-hole-size RSS in a point-the-bit configuration. The near-bit RPCC is measured 2.1 meters above the bit in the point-the-bit RSS. The RSVD sensor is located 2.8 meters above the bit. Optionally, a Pay-Zone Steering module is placed at the bit for inclination, RPM and Gamma Ray measurement.

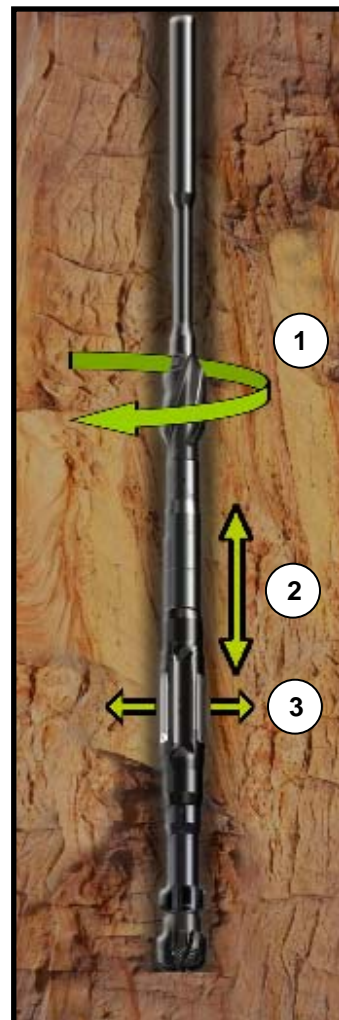


Figure 5: The near-bit vibration sensor has been integrated into this RSS, featuring detection of the three principal modes of drillstring vibration — 1) torsional, 2) axial, and 3) lateral.

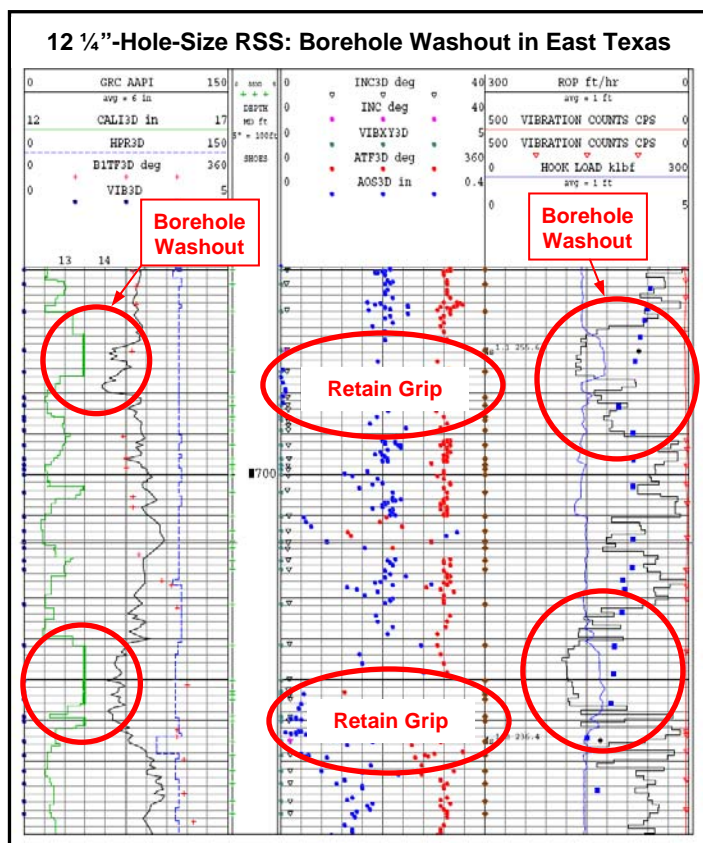


Figure 6: A typical borehole washout up to 13.5'+ in a soft unconsolidated formation at low inclination (1°~2°).

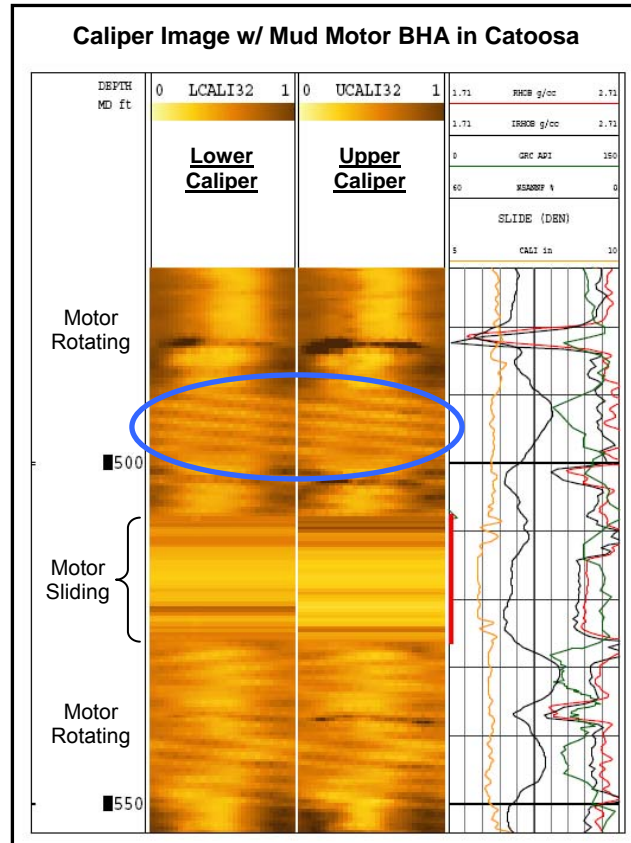


Figure 7: An example borehole spiraling in Tracks 1 and 2 observed in an azimuthal caliper image. The 2-to-3 feet "pitch" can be observed in a blue circled area.

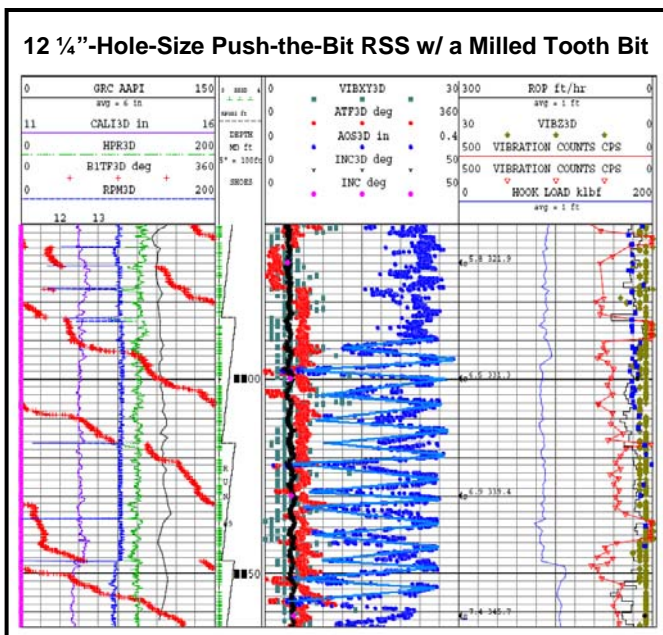


Figure 8: The sections drilled with a general-purpose milled tooth bit where suspected hole spiraling was observed.

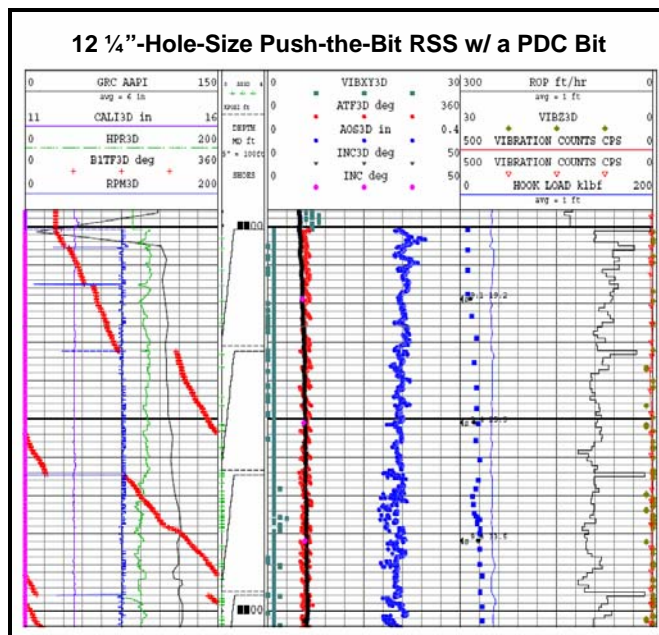


Figure 9: The sections drilled with the tapered gauge PDC bit matched with this particular RSS, where the suspected hole spiraling was eliminated.

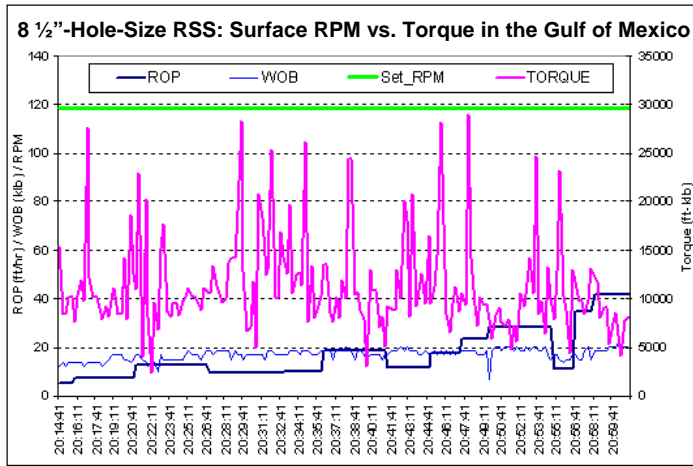


Figure 10: Surface parameters/data during downhole full-blown stick-slip. Notice that rotary torque fluctuations correlated highly with the downhole near-bit stick-slip data in the figure below (in **Figure 11**) while the WOB was kept nearly constant. The Set RPM is the programmed surface RPM that is different from the actual surface RPM.

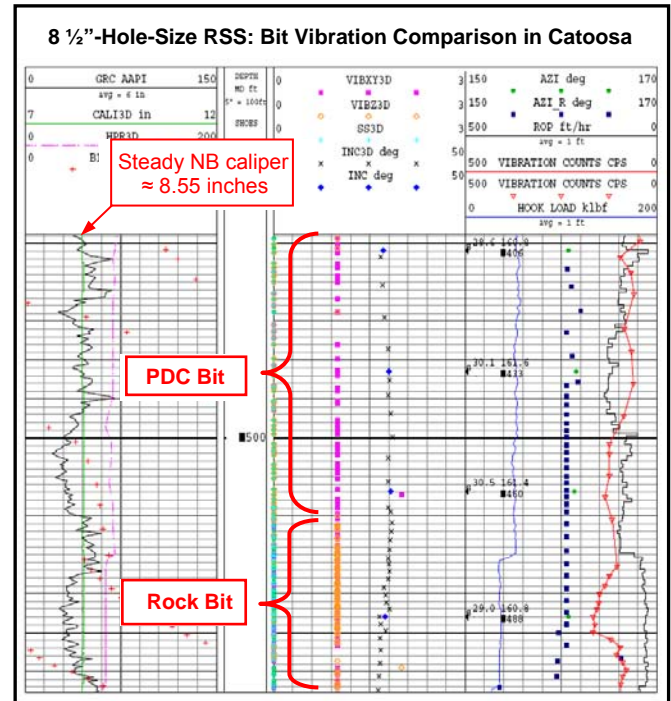


Figure 12: Vibration Comparison between PDC and Rock bit in the real-time MWD/RSS data. Lateral vibration (VIBXY3D = 1) was dominant while drilling with a PDC bit. In contrast, axial vibration (VIBZ3D = 1) was dominant with a rock bit.

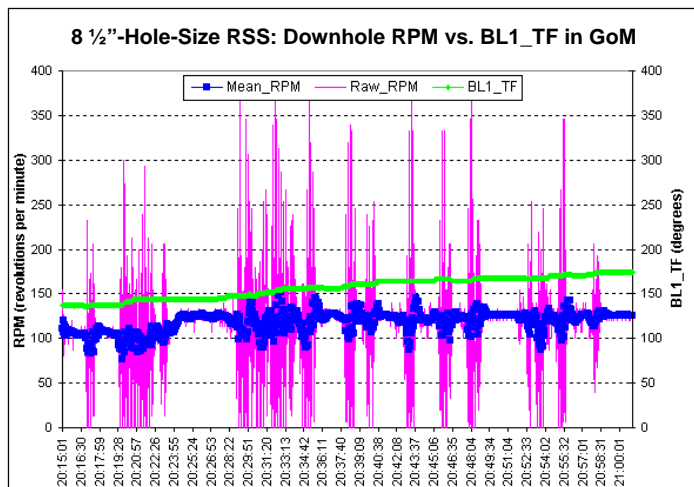


Figure 11: Downhole mean and raw RPM vs. blade housing toolface angle (BL1_TF). The slowly changing BL1_TF (140 ~ 170 degrees) indicates the non-rotating blade housing was substantially stationary, compared with the mean drillstring rotation (about 120 RPM). The raw RPM oscillations between 0 RPM and 380 RPM indicate the onset of a full-stall stick-slip. The corresponding Stick-slip Severity (SS%) in the period is between **200%** and **300%**.



Figure 13: An insert bit used with the 8 1/2-hole-size RSS.

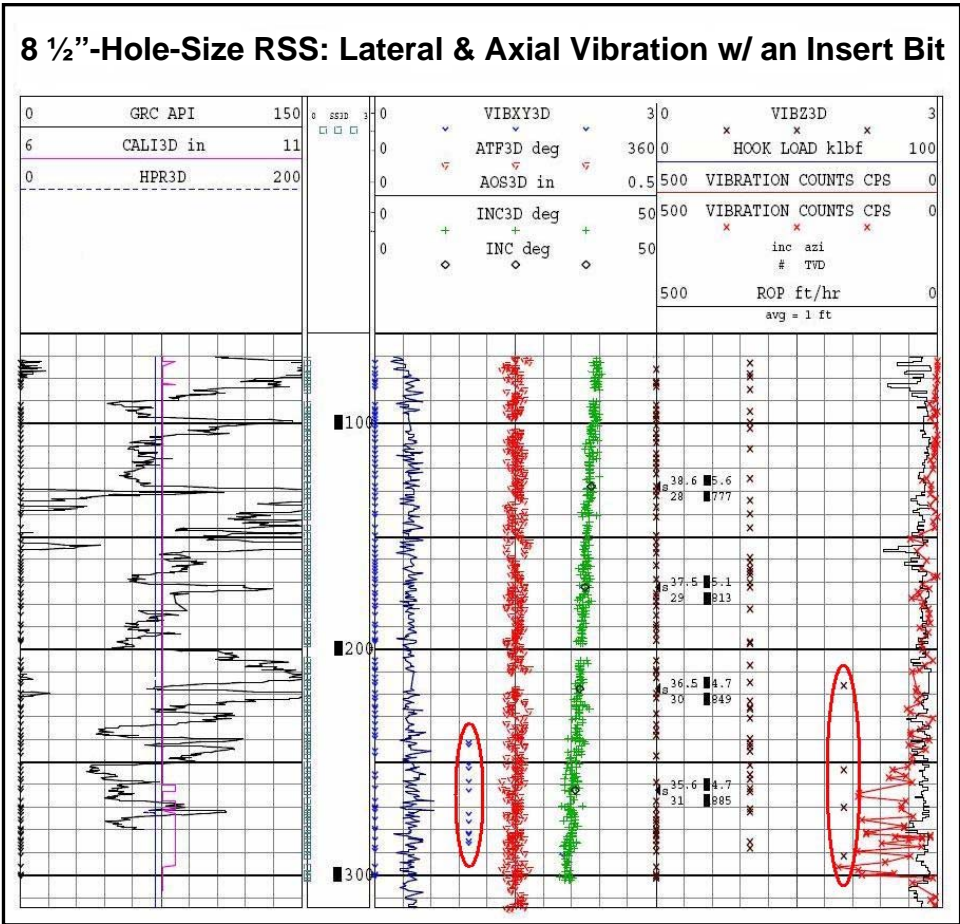


Figure 14: The sections drilled with an insert bit. The MWD and RSS vibration increased without obvious formation changes. The Real-time Stick-slip and Vibration Detection (RSVD) provided the RSS operator with an early alert of the bit and BHA instability



Figure 15: A dull bit in 8 1/2" ring indicates that the bit was more than 1" undergauge.



Figure 16: The side view of the insert bit with worn shirt tails.

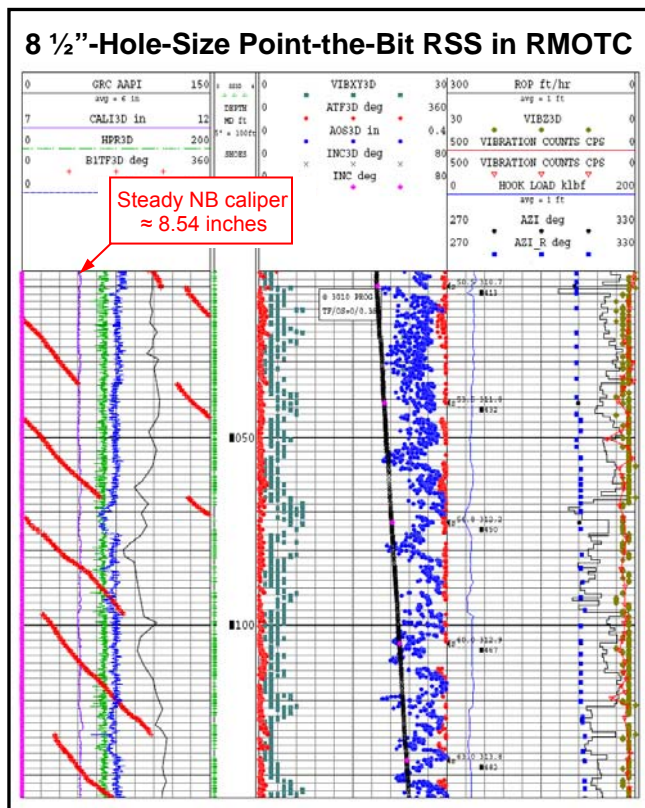


Figure 17: The maximum build rate test with an 8 1/2"-hole-size commercial point-the-bit BHA (w/ 98% offset).

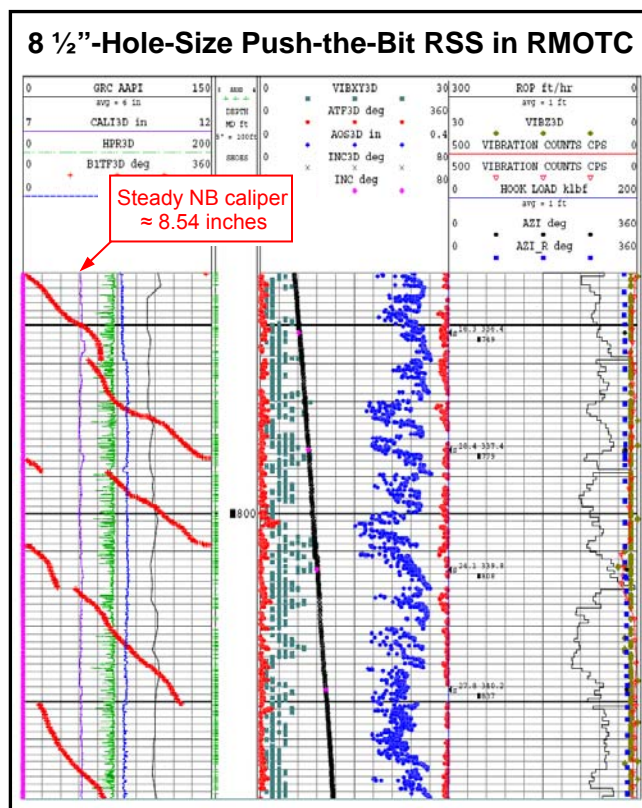


Figure 18: The maximum build rate test with an 8 1/2"-hole-size prototype push-the-bit BHA (w/ 88% offset).

	Point-the-Bit	Push-the-Bit
Drill Bit	Partial Ring Gauge	Full Active Gauge
Formation	Shale	Shale
Flow Rate	440 GPM	400 GPM
RPM	100	100
WOB	12Klbs	10 Klbs
Tool Offset	0.39" (98%)	0.35" (88%)
ROP	49.3 ft/hr	49.0 ft/hr
DLS	10.2°/100ft	11.5°/100ft
Build Rate	10.0°/100ft	11.4°/100ft
Mean Caliper	8.536"	8.544"
Caliper Deviation	0.020"	0.022"
Housing Roll	0.84 rev/hr	1.25 rev/hr
Lateral Vibration	6.6	6.5
Axial Vibration	2	1

Table 1: A comparison table of ROP, build rate, borehole conditions and vibration between 8 1/2"-hole-size point-the-bit and push-the-bit modes.

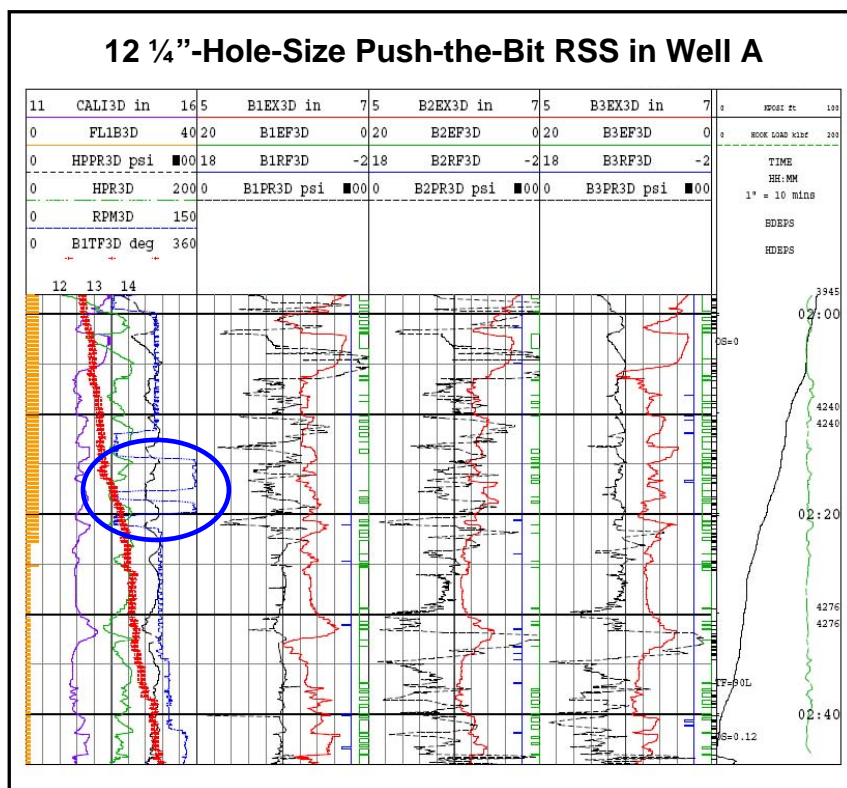


Figure 19: Memory data log during initial kick-off. The purple line on Track 1 indicates the caliper ranging from 12.5" to 13.0" while drilling ahead with a steady RPM. The blue line on Track 1 indicates on-bottom RPM programming while drilling ahead. The black line on the right (in Track 5) indicates the Kelly position.

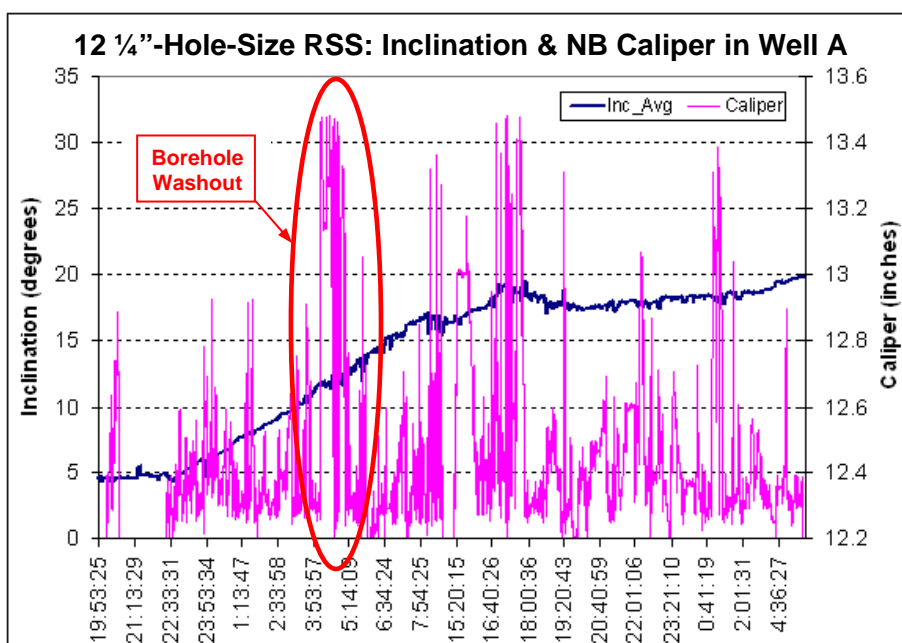


Figure 20: Inclination and near-bit caliper data through the build section. Caliper is erratic ranging from 12.25" to 13.5"; however, the build rate remains constant.

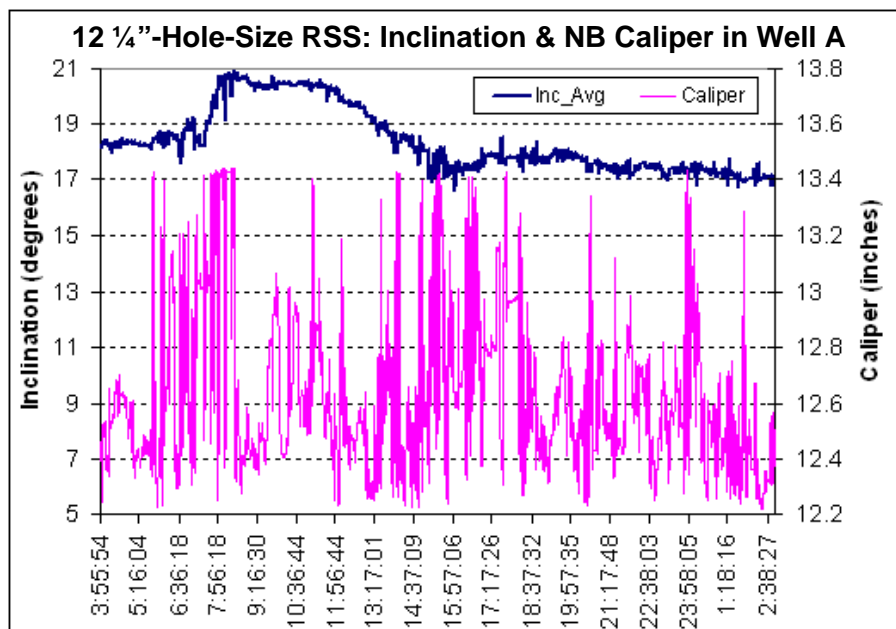


Figure 21: Inclination and near-bit caliper data through the tangent section. The caliper was very erratic but the tool managed to maintain inclination at approximately 18°.

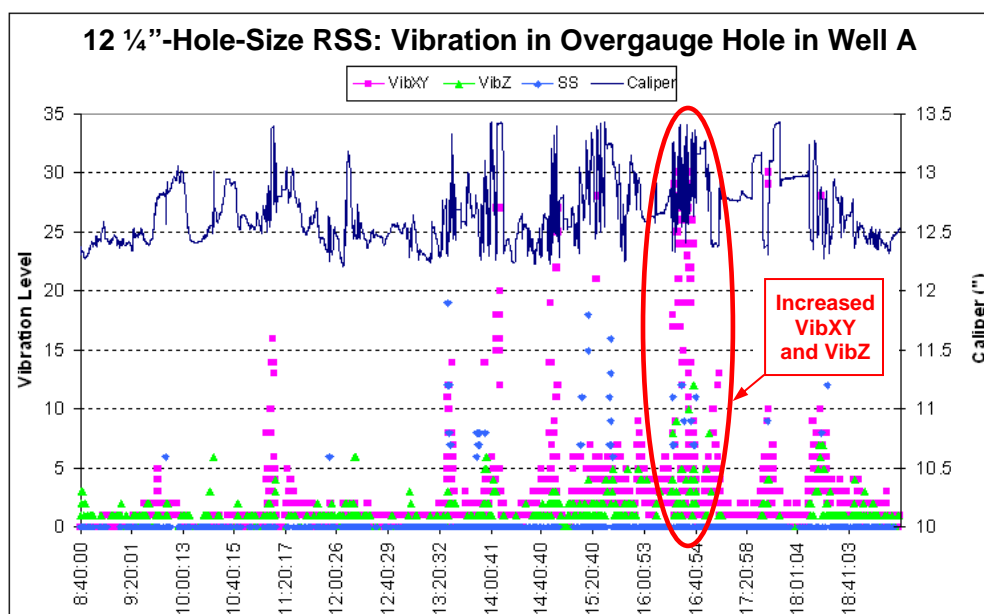


Figure 22: Vibration data in an overgauge hole. Lateral vibration (VibXY in pink) and axial vibration (VibZ in green) both increased in an overgauge borehole.

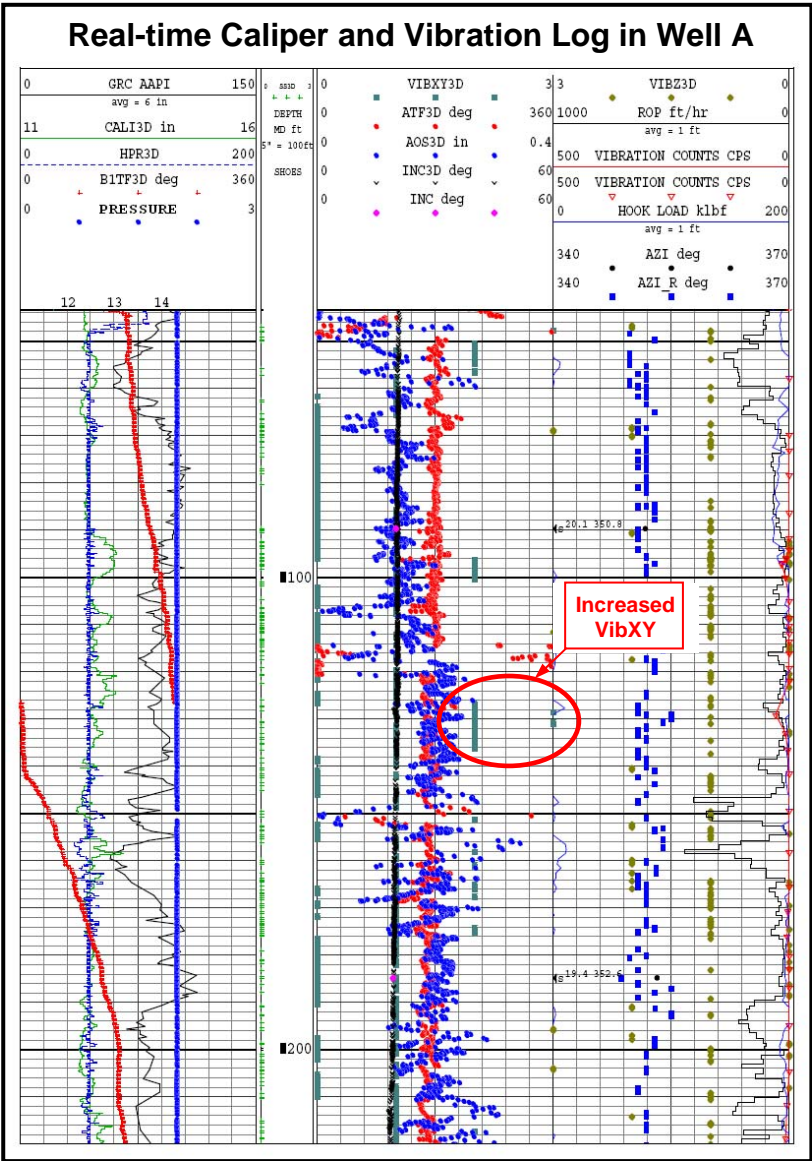


Figure 23: Real-time caliper and vibration data in an overgauged hole. Lateral vibration (VibXY in pink) and axial vibration (VibZ in green) both increased in an over-gauged borehole.



Figure 24: Lower rotating part of RSS BHA and drill bit from Well A. Clays in this area are very sticky and attach to the BHA.

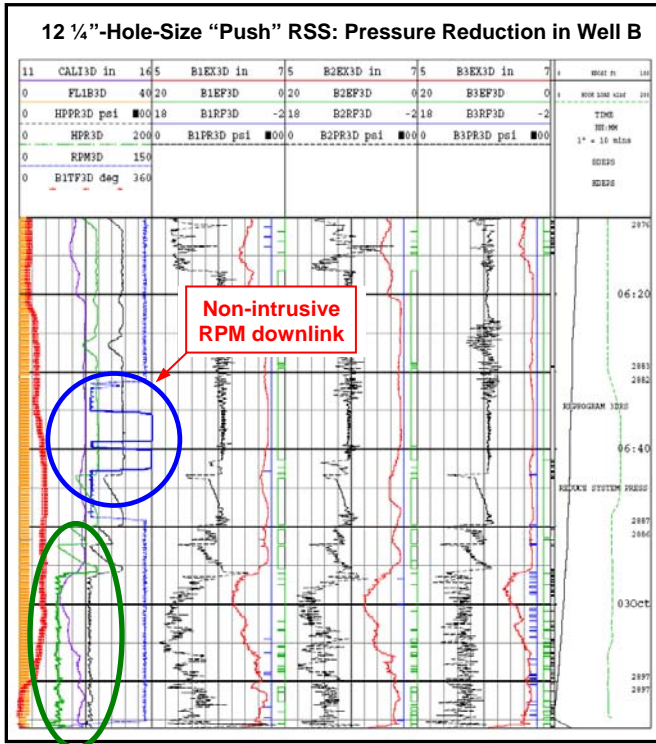


Figure 25: Memory Data Log from Well B. Near-bit caliper in purple (CALI3D in Track 1) indicates overgauge hole. RPM in blue (RPM3D) shows on-bottom downlink command to reduce hydraulic system pressure to 60%.

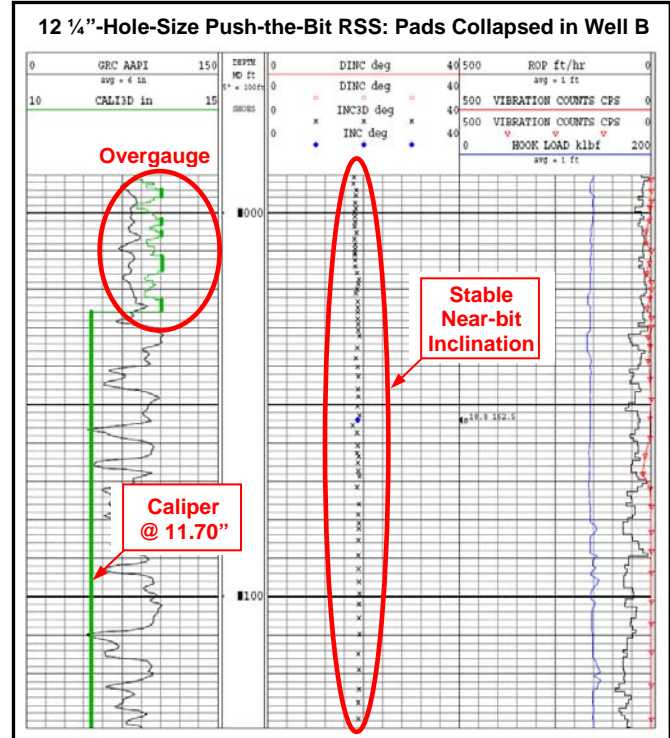


Figure 27: Real-time near-bit caliper log. RSS Pads are collapsed to test directional response. Green curve in Track 1 represents real-time pad-contact caliper (CALI3D). Assembly maintains inclination (INC3D) at approximately 18.8° as in Track 2.

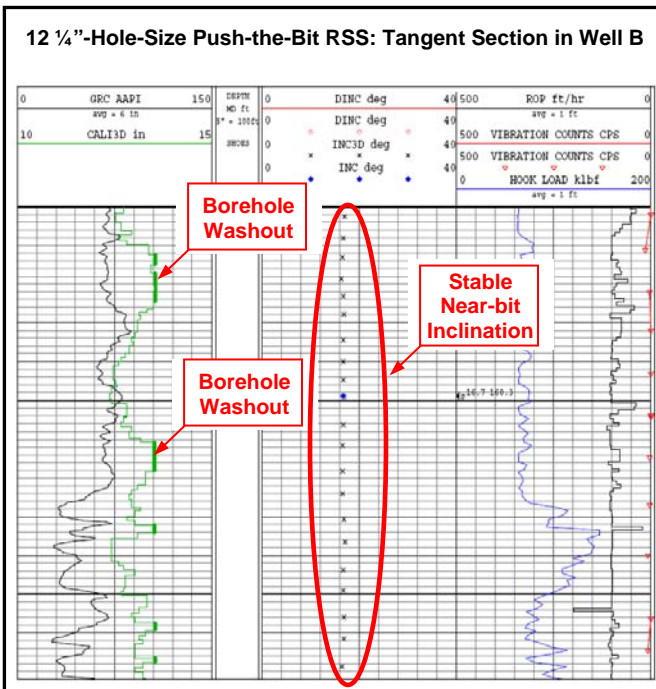


Figure 26: Real-time near-bit caliper log. Real-time pad-contact caliper (CALI3D) measurement is the green line in the left track. The caliper is varying from 12.5" to 13.5" and the RSS is still maintaining inclination (INC3D).

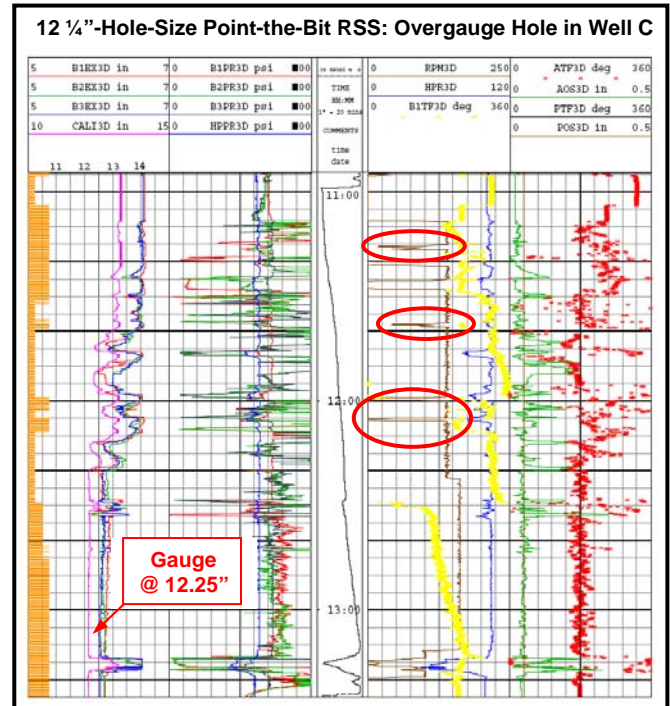


Figure 28: CALI3D (Pink Curve in Track 1) shows the near-bit caliper data in the Leine Potash. The caliper is erratic and above 13". When the Leine Halite is encountered at 12:20 hrs the caliper comes back into gauge at 12.25".

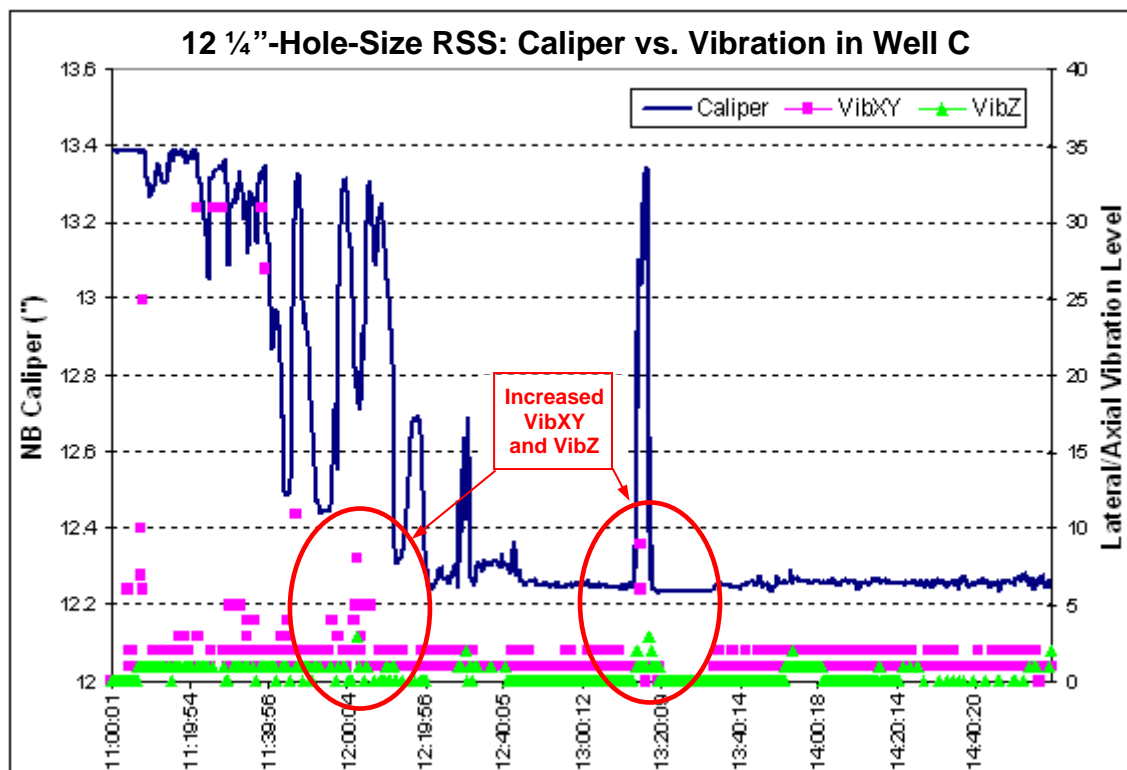


Figure 29: The near-bit caliper and vibration data in transition from Leine Potash to Leine Halite. As the Leine Halite was encountered at 12:20 hrs, the near-bit caliper (Caliper in blue) reduced to 12.25" on gauge. Lateral vibration (VibXY in pink) and axial vibration (VibZ in green) were both reduced in the gauged borehole in the Leine Halite.

MD (m)	TVD (m)	Inc (°)	Azi (°)	DLS (°/30m)	Build (°/30m)	Turn (°/30m)	TF (°)/OFFSET (%)
X733.5	X721.0	5.98	267.8	3.46	1.02	-35.2	90L / 43
X762.5	X749.8	6.42	240.7	3.03	0.46	-28.0	90L / 43
X791.5	X778.7	7.03	216.8	2.94	0.63	-24.7	90L / 43
X819.0	X805.9	8.79	202.3	2.89	1.92	-15.8	20L / 43
X826.5	X813.3	9.58	201.9	3.17	3.16	-1.40	20L / 43

Table 2: A Snapshot of Survey Data in Leine Halite from Well C.