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Hole Cleaning: the Achilles' Heel of Drilling Performance?

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Abstract

Field data confirm that hole cleaning is still a major problem on most directional wells and many vertical wells. This is despite significant progress made in drilling fluids, tools, and field practices, along with over 30 years of university and industry research. The more serious hole-cleaning problems can occur when potential risks are underestimated or not properly addressed, symptoms are ignored, rig personnel are not properly trained, drilling margins are too narrow, or high-performance bits and drilling fluids give a false sense of security at high penetration rates. Is hole cleaning the Achilles' heel of drilling performance, or are there opportunities at hand to yield step improvements?

This paper focuses on five recent Gulf of Mexico case histories that involve different aspects of hole-cleaning problems. Each case includes information on the hole-cleaning incident, tactics and results, and lessons learned. The captured lessons learned can be applied in other wells to mitigate hole-cleaning problems. The paper also incorporates suggestions into a framework of strategy and tactics to help resolve issues and rationalize hole-cleaning management. The concepts of strategy and tactics have military origins, but are commonly used in operations management and business in general.

Introduction

In 1971, Sze-Foo Chien made a memorable, animated presentation on annular velocities required for drilling operations.[1] With a map of World War II Europe as a backdrop, Chien used military strategy and tactics concepts to describe the industry's "war" on hole-cleaning problems. Field practice and extensive research conducted since that time have provided considerable insights into the hole-cleaning process, especially in horizontal and highly deviated wells. Some would argue, however, that the same research also has created a number of conflicting theories and controversies.[2] The indisputable fact, however, is that field data presented in this paper confirm that hole cleaning remains a major and costly industry problem.

During drilling, hole-cleaning problems can often be traced to truly unexpected events or improperly trained rig personnel. For example, high-performance drill bits, bottomhole tools and drilling fluids may give a false sense of security at high rates of penetration (ROP) and create a "High-ROP Trap". Also, failure to understand or properly interpret annular-pressure-while-drilling (APWD) data and the impact of drilling parameters on hole cleaning can be costly. Although various real-time measurement and simulation techniques designed to give an indication of the hole-cleaning efficiency exist, they are sometimes under utilized and fail to deliver true value to an operation.

Some of the most difficult situations arise when conditions exist or have deteriorated to the point where few options are available. Narrow drilling margins, for example, can negate increasing flow rates, mud rheology, or mud weight (in the case of wellbore instability). Or cold temperatures in deepwater drilling can prevent rheology adjustments in the absence of a flat-rheology system.[3] Or attempts to correct hole-cleaning problems can initiate other problems, such as barite sag.[4] Or controlled drilling can dramatically increase drilling time and well costs. On troublesome wells where practical options have been exhausted, hole cleaning can, in fact, become the Achilles' heel of drilling performance.

The focus of this paper is five recent hole-cleaning case histories drilled by different operators in the Gulf of Mexico involving water-based muds (WBM) and synthetic-based muds (SBM). Each case includes information on the hole-cleaning incident, tactics and results, and lessons learned. The lessons learned can be applied to other wells, including those outside of the Gulf of Mexico

Another goal of this paper is to demonstrate that Chien's warfare analogy can be exploited to provide a framework to help systematically resolve certain persistent issues. Hole-cleaning strategies and tactics are discussed primarily from an operations management perspective, although similarities to military operations are ever-present.

War Against Hole Cleaning Problems

Furthering Chien's analogy, warfare is inherently discussed using concepts of strategy and tactics. Strategy in general is defined as a "systematic plan of action to reach predefined goals"; tactics refers to "deploying and directing resources on an incident to accomplish the objectives designated by strategy". More simply, a "strategy" is what you "plan" to do, while "tactics" refers to "how" you are going to do it real time.

Within the context of this paper, strategy is the coordinated plan for applying the range of technologies and resources required to drill wells safely, efficiently, and cost-effectively. Tactics generally deal with addressing hole-cleaning and other problems encountered during the drilling process and the best available methods of mitigating the active problem.

It is difficult to generalize on the primary source of recurring hole-cleaning problems. Many serious hole-cleaning problems are caused by underestimation of potential risks or failure to properly address them at the onset in the well plan. Although hole-cleaning strategies seemingly depend on the well design, it is essential that hole-cleaning concerns be an integral part of the well plan.[5] On some critical wells, it is not uncommon for hole cleaning to be down on the priority list. Decisions on the well profile, casing program, drillstring, drilling fluid and properties, drilling window, available flow rates, and drilling mode are among those that could easily exacerbate hole-cleaning problems. Moreover, they could severely constrain tactics available to mitigate problems during drilling.

Critical well design also can benefit from interaction among multidisciplinary teams, especially if members from vendor organizations are included. It is important to get all team members involved. As will be shown later in the case histories, this is particularly difficult when drilling operations staff may not have the proper mindset.

Using these fundamental definitions, it can be argued that strategy can be equated with the drilling plan and tactics with individual, controllable wellsite operations. This is useful in looking at the many factors that impact hole-cleaning efficiency. Most of these are listed in Table 1. Also included are entries which attempt to broadly categorize each factor as part of a strategy or part of a tactic. A more specific distinction between the strategies and tactics that are or should be employed in hole cleaning is presented after the discussion of the five case histories.

Case History 1 – Synthetic-Based Mud

The well was drilled from a deepwater, tensioned-leg platform in the Mississippi Canyon area. A newly developed flat-rheology SBM was being used to drill the vertical 17.5-in. and the 14.5-in. build intervals. Experience with previous-generation SBMs indicated that yield points (YP) greater than 20 lb/100 ft^2 could cause lost circulation due to excessive ECDs. The new fluid was delivered with similarly low YP to avoid this problem.

Hole-Cleaning Challenge. The ECD gradually increased while drilling at elevated rates of penetration as shown in Fig. 1. At the same time, a gradual change in cuttings shape was noted (Fig. 2). Cuttings seen at the shale shakers were smaller and more rounded, indicating a longer residence time of the cuttings in the annulus.

Tactics and Results. The fluid was treated to increase YP and low-shear rheology with a polymeric (non-clay) viscosifier. The YP was increased from 18 to 28 lb/100 ft^2, and hole cleaning was improved significantly. Contrary to expectations, the ECD as measured by APWD gradually decreased after the treatment, indicating a reduced concentration of cuttings in the annulus (Fig. 1). It is possible for the ECD contribution due to cuttings to vary between 1 lb/gal to more than 2.5 lb/gal, depending on drilling conditions. APWD data of sufficient accuracy would therefore be imperative in order to properly assess treatment effectiveness.

Lessons Learned. The first learning was that in a hole-cleaning situation, increasing fluid rheology moderately could lead to a reduction in ECD. The application was also a good example of hole-cleaning monitoring. By carefully analyzing the cuttings shape and size and by comparing real-time ECD measurements with calculated ECDs, it was possible to quickly detect inefficient hole cleaning. Last, but not least, this example showed that a high-performance drilling fluid such as a SBM may create a false sense of security, leading to very high rates of penetration that may quickly create excessive cuttings load in the annulus.

Case History 2 – Water-Based Mud

This deep, shelf well was drilled from a jack-up rig in the Eugene Island area. The interval of interest was the 12.25-in. intermediate section from 4,610 to 11,352 ft drilled at a maximum angle of 50°. The drilling fluid used was a non-dispersed, inhibitive WBM. The fluid was delivered to the rig with a rheology considered typical for this hole size (Table 2).

Hole-Cleaning Challenge 1. Due to the inhibitive character of the WBM, high rates of penetration were achieved from the beginning of the section, as well as larger size cuttings and a virtually in-gauge wellbore. As drilling progressed, it was obvious that a portion of the drilled cuttings was not being brought to surface. This was confirmed when a short trip was made. Excessive drag prompted the operator to backream, and a significant amount of cuttings was recorded at the shakers.

Tactic 1 and Results. The fluid rheology was slightly increased and a high-viscosity sweep program was also implemented by the operator in an attempt to improve hole cleaning, which further increased fluid rheology until the YP was as high as 61 lb/100 ft^2 (Table 2). As drilling continued at similarly high ROPs, no improvement in hole cleaning was noted.

Hole-Cleaning Challenge 2. Following the increase in rheology, short trips with backreaming were continued as the amount of cuttings removed while drilling was still inadequate. Unlike when the fluid had lower rheology, large agglomerations of cuttings were circulated out, suggesting that the higher rheology in this case increased the severity of the hole-cleaning problem.

Tactic 2 and Results. A 20% dilution was applied to the active system to reduce the rheology and the amount of fine drilled solids incorporated in the system due to the numerous backreaming events. The cuttings agglomeration was virtually eliminated as the YP was brought at or below 40 lb/100 ft^2. As sweeps were still required by the operator to verify and correct hole cleaning, high-density sweeps were used in lieu of the high-viscosity sweeps. These sweeps were more effective in bringing the remaining cuttings to surface and did not generate an increase in fluid rheological properties. A post-well analysis confirmed that the cuttings agglomeration occurred only at YP values above 40 lb/100 ft^2.

Lessons Learned. Under good hole-cleaning conditions, an inhibitive WBM may generate cuttings very similar in shape and size to SBM cuttings. Under long residence conditions, WBM cuttings will gradually become softer, increasing the potential for cuttings agglomeration. High-viscosity sweeps are not recommended, especially in deviated holes. If a sweep is employed to verify / improve hole cleaning, this should be a high-density sweep. Hole-cleaning efficiency can be diminished if the rheology is excessive. Backreaming should be avoided as it can exacerbate the hole-cleaning problems. Backreaming not only promotes cuttings agglomeration and packing off; but as the drill string goes from a tension / compression to a tension-only state, the BHA will rotate on a different path and the bit and the stabilizers will generate new and larger cuttings on the trip out.

Case History 3 – Water-Based Mud

An operator drilled a number of shallow-water wells in the Vermilion area. A jack-up rig was connected to gas-producing platforms to drill high-angle sidetracks. The section in discussion was the 6.75-in. interval drilled approximately from 2,600 to 6,600 ft, at 60 – 71° inclination. On some of the wells, it was observed that the temperature effect on fluid rheological properties, resulted in reduced hole-cleaning efficiency at bottomhole conditions.

Hole-Cleaning Challenge. While the drilling fluids showed good shale inhibition in early wells, ROPs had to be controlled around 100 ft/hr to minimize hole-cleaning problems. When the ROP exceeded this limit, a rapid increase in cuttings concentration in the narrow annulus was observed, resulting in significant ECD increase (up to 2.5 lb/gal over the mud weight). The drilling had to be stopped temporarily to circulate all the cuttings out. As in the previous case history, cuttings with longer residence in the annulus showed a tendency to become softer and to adhere to each other or to the wall.

Strategy and Results. On subsequent wells, the strategy employed was to modify the fluid rheological profile by introducing a novel biopolymer in combination with a polysaccharide fluid-loss additive. The fluid exhibited rheological properties that were less temperature dependent in the 70 – 180°F range (Fig. 3), translating to less thinning at bottomhole temperatures. As a result, the ROP was able to be increased to an average of 175 ft/hr while rotating and 120 ft/hr while sliding. The other benefit of the new combination was a higher ratio of LSYP / YP (Table 3). This not only enhanced the velocity profile, but also allowed higher LSRV to improve hole cleaning without adversely affecting ECDs or promoting cuttings agglomeration.

Tactics and Results. Further progress was made by fine-tuning the drilling practices and communication at the rigsite. ECD was monitored more closely and broadcast on the rig paging system periodically with the mud weight to raise awareness and encourage faster reaction to potential problems. High-viscosity sweeps were eliminated. Occasionally, when the ROP exceeded 200 ft/hr, the bit was picked off bottom and 1 – 2 bottoms-up circulations were made to effectively clean the hole. High-density pills were used only in two instances to verify good hole cleaning.

Lessons Learned. This application exemplified how the fluid formulation can be adjusted in the planning stage to provide significant improvement in hole cleaning. The case also highlights how important is to ensure proper communication at the wellsite and to make full use of the real-time ECD measurements.

Case History 4 – Synthetic-Based Mud

This well was part of an extended drilling program from a production platform in the shallower waters (~1,000 ft) of the Mississippi Canyon area. Wells were being drilled at 50 – 75° angle; tangent sections lengths exceeded 10,000 ft. As is often the case in the latter stages of production platforms, well complexity was increased to allow further reach to additional reserves.

Hole-Cleaning Challenge. While drilling at up to 200 ft/hr instantaneous ROP, the cuttings dryer used to reduce synthetic retention on cuttings plugged up and was taken off line. It was decided to stop circulation immediately to avoid non-compliant discharges. The wellbore was left static for the several hours required for maintenance on the dryer. When circulation resumed, a severe pack-off occurred requiring working the pipe and backreaming out of the zone. After drilling resumed, the ECD and the torque gradually increased, leading to a second pack-off followed by lost returns. The losses were eventually cured, but other pack-off incidents occurred. Also, the amount and size of cavings at the shakers noticeably increased. The wellbore became very unstable. and it was decided to re-drill the entire section.

Tactics and Results. The re-entry was drilled with a WBM. The fluid was not as inhibitive as the SBM, and the ROP was inferior to what was achieved with SBM. However, due to the fact that no wellbore instability occurred this time, the sidetrack was drilled in an average of 3.64 days/1,000 ft, compared to 5.58 days/1,000 ft.

Lessons Learned. This application highlights the "High-ROP Trap" illustrated in Fig. 2, which was found to be the cause of other failures on offset projects. The "High-ROP Trap" occurs when high-performance drilling fluids or tools promote very high penetration rates, that unfortunately are excessive for effective hole cleaning. Although the failure in finishing the original interval was perceived as wellbore instability, the root cause was a hole-cleaning problem that was not corrected prior to stopping circulation for several hours. This hole-cleaning problem eventually triggered wellbore instability due to high ECDs and repeated disturbances during working the packing off which (a) forced fluid penetrating into shale microfractures, and (b) directly loosened an originally weak formation near a fault. Increased mud weight after the hole problem had already started did not appear to relieve the problem.

When hole instability near a weak zone is instigated, it can make hole cleaning very difficult, if not impossible, because the aggressive pipe movement required for proper hole cleaning can contribute to hole collapse. While this was a case where hole cleaning triggered wellbore instability, it should also be noted that there have been instances when the opposite has been true. Wellbore instability usually results in excessive amounts of cuttings and cavings, which are often regarded as the result of simply not cleaning the hole effectively.

Case History 5 – Synthetic-Based Mud

This shelf well was designed as a "quick hit" to produce known reserves in shallow water. Hole cleaning problems arose in the 50° portion of the well and resulted in a stuck rotary steerable tool. A sidetrack was carried out after unsuccessfully trying to retrieve the fish. In reality, the preceding intermediate section (35° angle) was not properly cleaned and contributed to "an avalanche effect" at the high ROPs indicated.

Hole-Cleaning Challenge. Fig. 5 shows an ingenious crossplot of relevant drilling and geologic parameters. Comments are provided from the driller's daily log. Drilling at up to 150 ft/hr average ROP (200 ft/hr instantaneous), this hole should have been short tripped at least every 1,500 ft from 5,000 to 13,000 ft; it was not. Weighted (not viscous) sweeps also would have helped. High-viscosity sweeps were pumped, but these tended to consolidate the cuttings bed. The result was stuck pipe and a subsequent sidetrack.

Tactics and Results. The sidetrack was successfully executed at lower ROPs combined with better attention to the downhole tools and mud properties. Even though rotary steerable tools should aid cuttings transport as compared to sliding drilling, they sometimes tend to be too aggressive both from the ROP standpoint and also from creating sloughing of weak zones. As stated, wellbore instability usually results in excessive cuttings loading especially at intermediate and high angles. Whenever possible, turbulence should be encouraged under these conditions through a combination of weighted sweeps at maximum pump rate (high Reynolds number) and pipe rotation.

Lessons Learned. Communication was sadly lacking in this project. Modeling help (pre-well and real-time) and problem analyses were provided by the technical support group only after the fact - a very costly lesson on the need for collaboration. In this case, hole cleaning was indeed the Achilles' heel as it resulted in the loss of 25 days of drilling time and ~$3 million extra cost to the well.

Hole-Cleaning Strategies and Tactics

The above field cases offer examples of various tactics, some more effective than others in improving hole cleaning. Too often hole cleaning is not made an intrinsic part of the overall drilling strategy. In one case, redesign of the drilling fluid improved rheological properties and therefore hole cleaning, as a part of the planning process of the next drilling project.

Choices made at the onset in the different well plans often are the most important, since implementing a strategy is normally associated with the expectation that it will be maintained throughout. Consequences of these choices and assumptions involved determine the type and scope of tactics available to mitigate problems during drilling.

Drillers rarely are involved in decisions on where, why, and when to drill. Nonetheless, critical well design can benefit from the interaction among multidisciplinary teams, especially if members from vendor organizations are involved. It is important to get all team members involved. As shown in the case histories, this is particularly difficult when staff directly involved may not have the proper mindset.

Although hole-cleaning strategy seemingly depends on the well design, it is essential that hole-cleaning concerns be an integral part of the well plan. Moreover, each factor affecting hole cleaning should be considered in context with other factors and the entire well plan. As such, overall strategies should be based on known or expected downhole conditions and preferably evaluated with fit-for-purpose simulation programs.[6] For example, turbulent flow normally is not achievable in large-diameter annuli. Flow rates and mud viscosity must be limited when drilling margins are narrow. And, "flat" rheology is desirable when drilling ultra-deepwater wells with synthetic-based muds.[7]

Perhaps the most serious hole-cleaning problems are caused by underestimation of potential risks or failure to properly address them during planning. It is not uncommon on certain critical wells for hole cleaning to fall on the priority list. Decisions on the well profile, casing program, drillstring, drilling fluid and properties, drilling window, available flow rates, and drilling mode are among those that could be adjusted to lessen expected hole-cleaning problems, or at least not constrain tactics to mitigate problems during drilling.

Consequences of drilling fluid selection can be particularly far reaching. Muds basically are selected according to performance, cost, and environmental concerns. All three factors are highly well dependent, but performance and cost requirements also depend on the particular well interval. While mud type inherently affects strategies for hole cleaning, some muds have a bigger impact than others. Available range of rheological properties, solids tolerance, interaction with cuttings (inhibition and suspension) and cuttings beds (gel structure), available flow rates (pressure losses and shear thinning characteristics), and annular velocity profiles are among the critical factors that should be considered when deciding the hole-cleaning strategy.

The false sense of security associated with the use of high-performance drilling tools and fluids can lead to the "High-ROP Trap", and negate any improvement, or even prevent well completion. In this case hole cleaning does become Achilles' heel of drilling performance.

Conclusions

1. Five recent Gulf of Mexico case histories confirm that hole cleaning is still a serious drilling problem with water-based and synthetic-based drilling fluids.
2. Hole-cleaning optimization is too often treated as a tactic and ignored as a strategy.
3. The best hole-cleaning strategy for a given well is highly dependent on the specific application, so care should be taken when trying to categorically apply this strategy on dissimilar wells.
4. Increasing mud rheology can reduce ECD if hole-cleaning efficiency is simultaneously increased.
5. Even on wells where elevated mud rheology improves hole cleaning, there is a limit whereby higher rheology can have a dramatic opposite effect.
6. Tools are available to monitor hole-cleaning efficiency at the wellsite; however, their value can be negated if results are ignored or improperly interpreted.
7. High-performance drilling fluids, bits, and downhole tools can promote excessive penetration rates for short periods and mask cuttings accumulations that can later result in serious hole-cleaning problems.
8. There are instances where hole cleaning can exacerbate wellbore instability and vice-versa.
9. As expected, weighted sweeps are more effective than viscosified sweeps in directional wells.
10. Communication among drilling team members and rig personnel is critical to mitigate and correct severe hole-cleaning problems.
11. There are certain troublesome wells where options are exhausted and hole cleaning can become the Achilles' heel of drilling performance.

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Table 1 – Factors Affecting Hole Cleaning and Their Primary Function as a Strategic or Tactics Tool

Factor	Category	Dependency	References
Annular dimensions	Strategy	Well design	8
Hole angle	Strategy	Well design, reservoir target	8, 11, 12
Temperature profile	Strategy	Well design, location	7
Drilling margin	Strategy	Well design, casing program	7
Mud type	Strategy	Well design, environmental	8
Mud composition	Strategy	Mud type, formation	3
Mud inhibition	Strategy	Formation characteristics	10
Cuttings characteristic	Strategy	Formation characteristics	10
Cuttings bed characteristic	Strategy	Formation characteristics, mud	3
Mud weight	Tactic	Well design, wellbore stability	13
Rheological properties	Tactic	Mud type	8
Rheological behavior	Tactic	Mud type	3
Annular velocity	Tactic	Drilling margin, rig equipment	8
Velocity profile	Tactic	Mud type, eccentricity	10
Penetration rate	Tactic	Drilling margin, problems	8
Flow regime	Tactic	Erodability, drilling margin	10
Cuttings-size distribution	Tactic	Bit, inhibition, stability	8
Cuttings size, shape	Tactic	Bit design, inhibition	11, 12
Drillstring rotary speed	Tactic	Motor, directional control	11, 12
Drillstring eccentricity	Tactic	Well profile, WOB, drillstring	11, 12
BHA, bit design	Tactic	Downhole tool cross section	9
Remedial operations	Tactic	Problems, drilling margin	6

Table 2 –Initial, Minimum and Maximum Rheology, Case History 2

Drilling Fluid Properties	Initial, As Displaced	During Drilling	
		Minimum Rheology	Maximum Rheology
Mud Weight (lb/gal)	10.3	13.0	13.55
Funnel Viscosity (sec/qt)	57@115ºF	65@88ºF	122@125ºF
Rheology Temp. (ºF)	120	120	120
600-rpm Reading	80	84	191
300-rpm Reading	54	52	126
200-rpm Reading	43	39	104
100-rpm Reading	29	25	71
6-rpm Reading	8	4	23
3-rpm Reading	5	3	17
PV (cP)	26	32	65
YP (lb/100 ft^2)	28	20	61
Gels (lb/100 ft^2)	8/10/11	4/8/11	19/23/27
API Fluid Loss (mL/30 min)	3.0	2.8	2.9
HTHP Fluid Loss (mL/30 min)	12@250ºF	9.8@250ºF	6.2@250ºF
pH	9.9	9.8	9.1
MBT (lb/bbl)	5.0	22.5	17.5

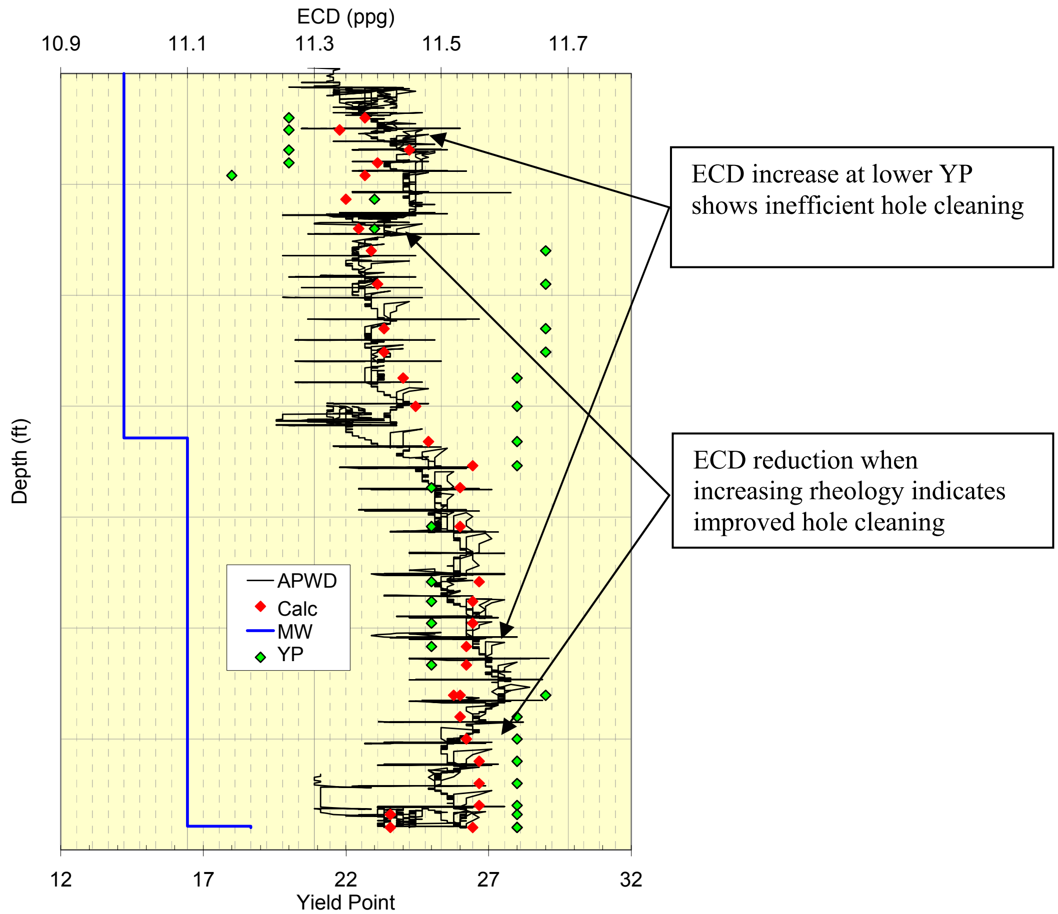

Fig. 1 – Measured and calculated ECD, mud weight and yield point, Case History 1.

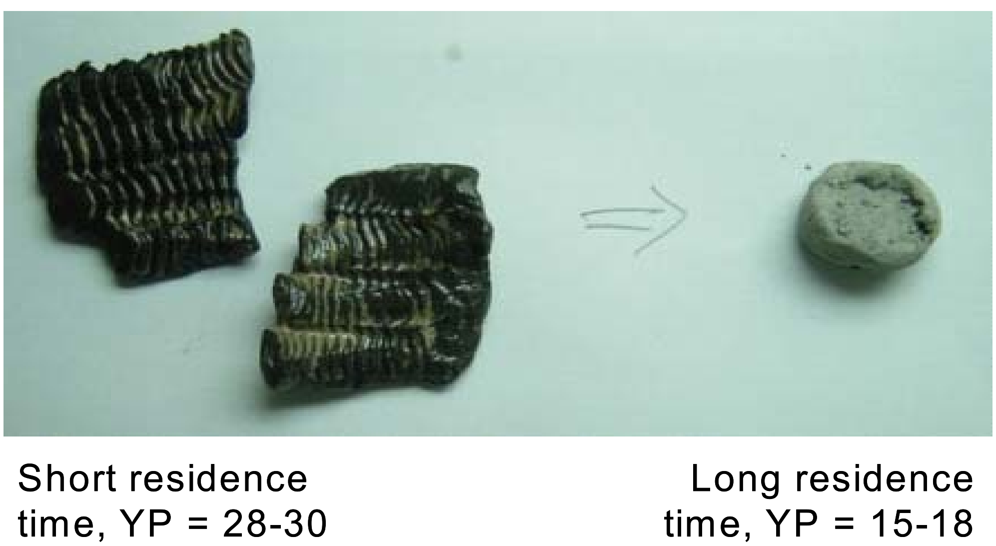

Fig. 2 – Change in size and shape of SBM cuttings with hole cleaning affected by rheological properties, Case History 1.

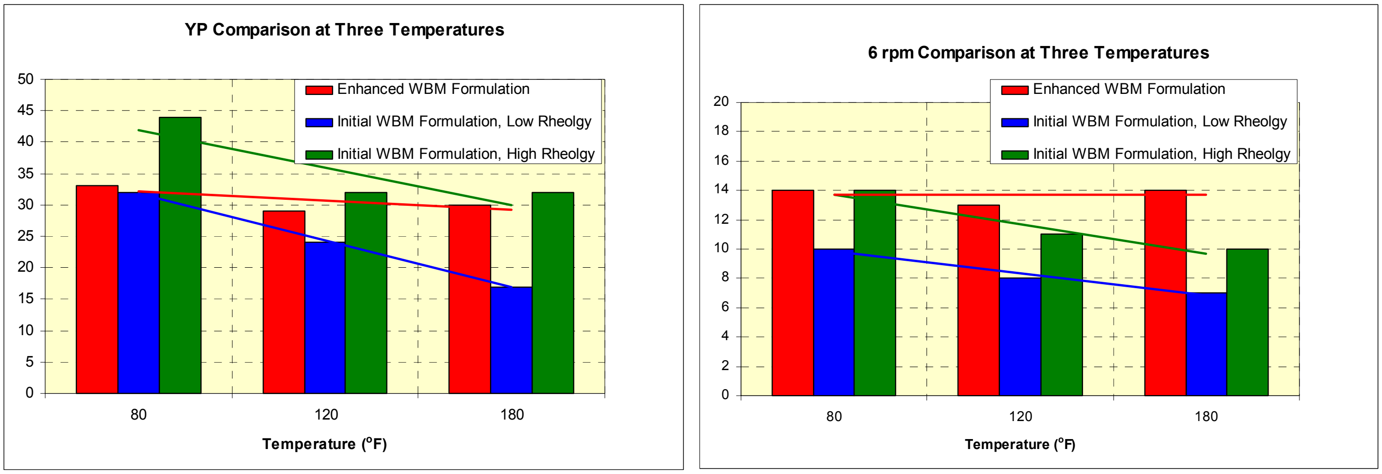

Fig. 3 – Effect of temperature on rheological properties for initial and enhanced WBM formulation, Case History 3.

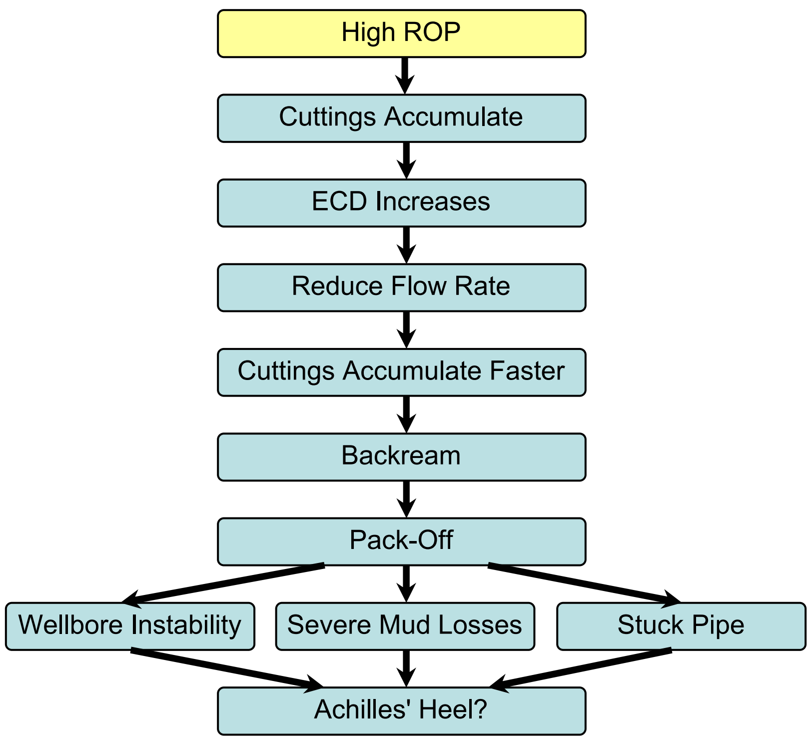

Fig. 4 – Graphic representation of the "High-ROP Trap", Case History 4.

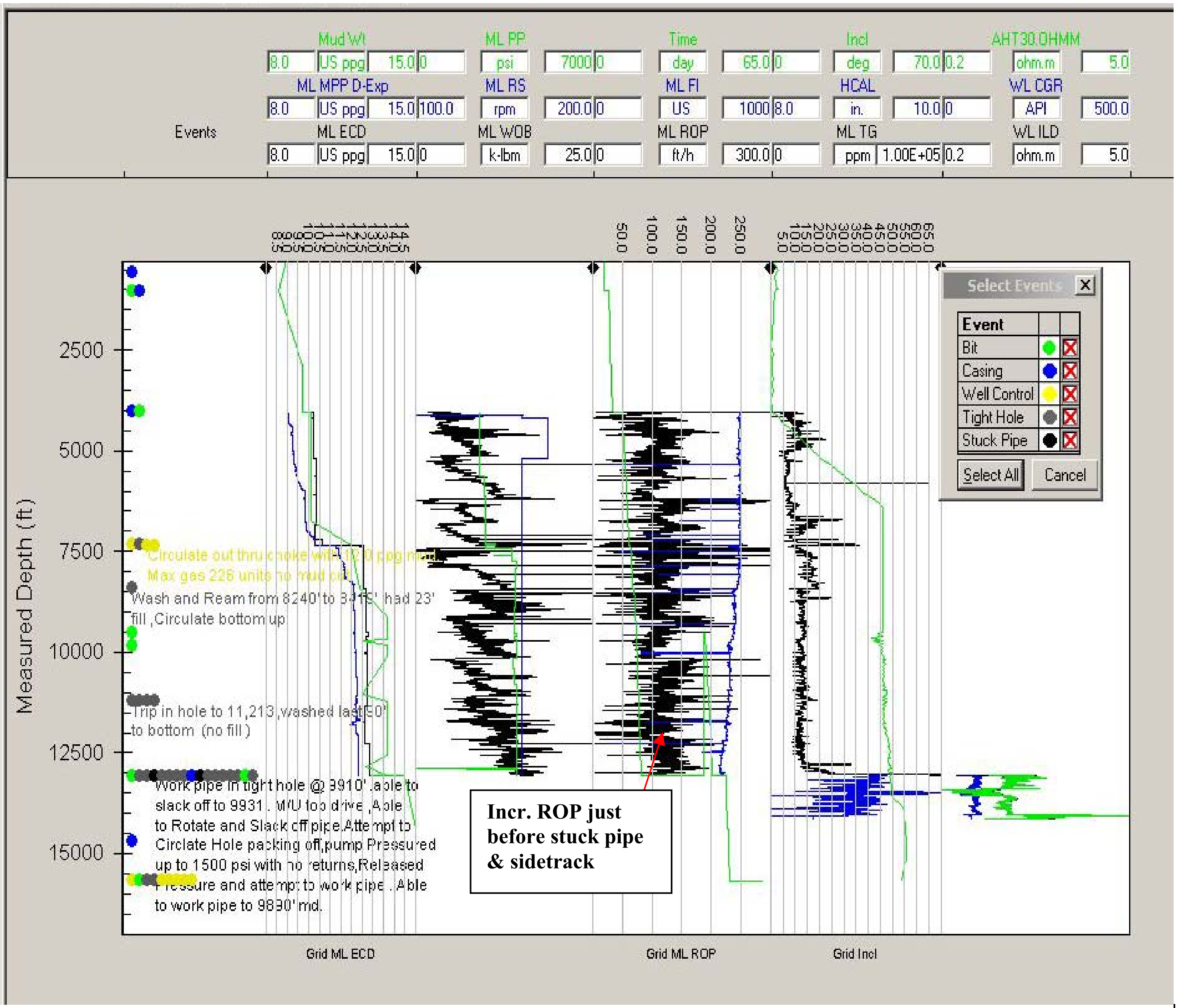

Fig. 5 – Correlative analysis of hole-cleaning and other drilling problems – GOM Shelf Well, Case History 5.