259

Real-Time Hole Cleaning Index Improves the Rate of Penetration by Monitoring the Cutting Concentration in the Annulus During Drilling Operations

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ABSTRACT

Drilling operations are critical and expensive for extracting an accumulated hydrocarbon in reservoirs. To implement cost reductions in drilling operations, the wells must be completed and delivered within the optimum time and cost. To achieve the planned optimum time and cost efficiency for drilled wells, we need to reduce the drilling time, which is influenced by the ROP of the section. ROP is defined as the speed of drilling and the amount of volume of drilled rocks displaced to penetrate more formation to achieve the target rate. ROP is greatly affected by hole cleaning optimization and the smooth transport of generated cuttings from the well; the greater the cuttings build up, the slower the ROP due to a change in ECD while drilling. The cutting concentration in the annulus (CCA) is an effective tool for monitoring and measuring hole cleaning efficiency and can greatly influence the ROP. It can also be used to predict the maximum limit of ROP, which can be reached safely without inducing further downhole problems such as stuck pipe, erratic torque and drag, and lost circulation incidents due to cuttings accumulating and overloading the annulus. The objective of this paper is to introduce a real-time hole cleaning algorithmic model by using automated and modified cutting concentration in the annulus that can provide an automated profile of the hole cleaning performance during drilling operations, which would provide cost savings and drilling efficiency. There are several models, correlations, charts, chemical additives, tools and methodologies; however, most of them are experimental tests, lack practicality and are not feasible in drilling operations. Offset parameters and factors from several fields were collected, analysed, validated and automated to facilitate a new real-time hole cleaning indicator to ensure continuous and automated monitoring and evaluation of the generated algorithmic model for hole cleaning performance during drilling operations that can also allow intermediate intervention for the drilling team. The surface real-rig time sensor readings and surface drilling fluid properties and measurements can be utilized and uploaded by the model that has been evaluated and validated with offline real-time readings and applied in the field while drilling. The model can show the real-time profile of the CCA, which can provide an illustrative and understandable vision of the downhole hole cleaning efficiency and optimize ROP that can be implemented without affecting well drilling performance. The results of the developed real-time algorithmic model enhanced the drilling efficiency with a 48% improvement in ROP.

EXTENDED ABSTRACT

Drilling operations are major procedures to extract accumulated hydrocarbon found in the reserves. Drilling is a consumable expenditure, and drilling time is crucial to minimize drilling costs. To drill quickly, hole cleaning efficiency is a critical parameter in drilling operations to enable drilling teams to obtain optimized results. Hole cleaning is the ability to clean the drilled hole section from generated cuttings while drilling. It remains a challenging task when planning and drilling vertical and directional wells. Hole cleaning in directional wells requires continuous supervision for all drilling operations with consumed time, delayed logistic tasks, uncontrollable usage of drilling fluid additives and high amounts of diluted water or safra oil to be used for controlling drilling operations. Several controllable and uncountable factors can impact the hole cleaning efficiency, as shown in Table 1. There are several hole cleaning indicators, such as the carrying capacity index (CCI), transport ratio index (TRI), transport index (TI) and cutting concentration annulus (CCA). All the previous indictors are limited to vertical wells. If drilling cuttings in the annulus are not controlled and transported from the drilled hole section, this could lead to massive drilling troubles, such as coincident stuck pipes due to poor hole cleaning, lost circulations and eventually well control incidents. Evaluation of the cutting concentration in the annulus (CCA) will help significantly enhance the down hole cleaning performance and indicate whether there will be more cuttings due to shale caving and sloughing. CCA can also be used to gain clear insights into whether the rate of penetration (ROP) should be controlled or optimized. CCA can provide warning of wellbore instability, diagnose the deformation mechanism and integrate caving information with other measurements, such as adjusting drilling fluid density for controlling shale caving by providing mechanical applied force to stabilize the produced bed collapse or due to cleavages in preexisting fractures or join sets. CCA will support the smooth and successful completion of drilling of the hole section to the casing point. Tables 2 & 3 illustrate typical and common drilling formation top equivalent densities and their lithology. Many studies have been conducted to understand the factors that affect hole cleaning efficiency. Pigott (1941) identified the parameters that can influence cutting transport of drilling fluid. Williams and Bruce (1951) estimated the minimum annular velocity to remove cuttings from the hole. Newitt et al. (1955) calculated the cutting concentration in the annulus based on annular velocity, and they concluded that the percentage of cutting concentration should not be more than 5%. Mitchell (1955) suggested a new method to calculate cutting concentration in the annulus if circulation stops due to making connections per stand. Hemphill and Larsen (1996) performed an experimental study to compare the WBM and OBM to provide hole cleaning efficiency in deviated annuli at various annular velocities. Sanchez et al. (1999) explained the significant effect of drill pipe rotation on cutting transport that accumulated on the low side of the hole section of direction drilling. The newly developed model was based on the original cutting concentration in the annulus that was developed for vertical wells only. The new model can be used to evaluate the drilling cuttings generated while drilling in deviated and horizontal wells. To develop the CCA model for directional wells, one section in Field A was selected, consisting of a sandstone formation and a limestone formation, which is a hard formation, as shown in Table 4 and is usually drilled by using a PDC bit with a size of 8.5”. The data were cleaned and filtered to check the critical parameters that can influence CCA while drilling were determined. Mechanical parameters and drilling fluid rheological field to combine them with the hydraulics of velocities were used to integrate them with mechanical drilling and drilling fluid parameters. The developed CCA model was derived from the original CCA model that was developed by the American Petroleum Institute (API) and is composed of mechanical drilling parameters, drilling fluid properties and drilling hydraulics drilling velocities. The model was developed and applied in the field to compare an offset well that had low ROP due to poor hole cleaning and an optimized well that used the developed model to optimize ROP due to the achievement of optimized hole cleaning efficiency by using the developed model for evaluating and allowing immediate intervention. The modified model contained several important parameters that were not used in previous hole cleaning models. The modified model was applied in two wells in the directional 8.5 ‘’ hole section with inclinations from 70 degrees to 90 degrees in the same offshore platform with the same drilling features, scenarios and drilling bottom hole assembly (BHA) design, as shown in Tables 5, 6 and 7. The list of abbreviations can be found in Table 8, and the results of improved ROP by 48%, average cutting size prediction, effective drilling fluid density, average drilling cutting densities, cutting concentrations in the annulus with two limits (cutting concentration in the annulus window) and estimated equivalent circulating density can be clearly seen in Figure 1. The average ROP in the offset well was 94 (ft/hr), while that in the trail or optimized well was 140 (ft/hr) due to the enhancement of the hole cleaning efficiency while drilling and placing lower and upper limits for the cutting concentration in the annulus between 0.03 and 0.05 to achieve smooth and controllable drilling and effective cleaning of the hole section without jeopardizing the drilling efficiency. The steps to develop the model are as follows: 1- Calculate drilling cuttings rise velocity by using drill pipe and hole section sizes and ROP. Drill cuttings size can be calculated, and if a drilling motor is used, consider rev/gal of the motor’s specification. Calculate drilling cutting transport velocity due to gravitational force by using drilling cutting size and density (22.5 PPG). Calculate the cutting slip velocity for the turbulent flow regime by using the drilling cutting size, cutting density and drilling fluid density. 2- Calculated modified average annular velocity by using cutting rise and cutting transport velocities with hole angle influence. The flow behavior index and consistency index were calculated by using viscometer readings at 600, 300, 6, and 3 RPMs. Calculate the apparent viscosity of the drilling fluid by using flow behavior and consistency indices and the modified average annular velocity. The cutting slip velocity is calculated for the laminar velocity by using the ROP, cutting size and density, drilling fluid density, drill string rotation, flow behavior index and apparent viscosity under the influence of the hole angle. Calculate the developed cutting concentration in the annulus by using the ROP, hole size, modified average annular velocity, cutting slip velocities for laminar and turbulent flow regimes and drill pipe size. 3- Calculate the effective drilling fluid density with the effect of cuttings generated in the annulus while drilling. The average cutting density was calculated. Calculate the equivalent circulating density with the influences of cuttings and pressure loss friction in the annulus. The steps are summarized in the flow chart diagram.

Table -1 shows the factors and their impacts.

Factors	Remark	Impact
Hole section size	Uncontrollable	Moderate
Hole section washout	Uncontrollable	Minor
Drill pipe diameter	Uncontrollable	Minor
Mud pump flow rate	Controllable	Major
Drill string rotation	Controllable	Major
Drill string eccentricity	Uncontrollable	Moderate
Mud rheology	Controllable	Major
Well trajectory	Uncontrollable	Moderate
Sliding drilling	Uncontrollable	Minor
Rate of penetration	Controllable	Major
Wellbore instability	Controllable	Moderate
Mud solids	Controllable	Minor
Water depth	Uncontrollable	Moderate

Table 2: Typical Matrix and Fluid Densities

Substance Density (g/cc)	
Sand-stone	2.65
Lime-stone	2.71
Dolomite	2.87
Anhydrite	2.98
Halite	2.03
Gypsum	2.35
Clay	2.7 – 2.8
Fresh-water	1
Sea-water	1.03 – 1.06
Oil	0.6 – 0.8

Gas	0.015

Table 3 clarifies the most common formation lithology used as casing seats in drilling.

Description of Rock Types	
Dolomite	Another Form of limestone, usually hard and occurs in crystalline and non crystalline forms with a density of 2.86 g/cc. Dolomites, CaMg (CO3)2, are formed by substitution of magnesium carbonate for a portion of the original calcium carbonate. Usually, a very good casing seat unless it is a hydrocarbon bearing rock.
Gypsum	Belongs to the group of rocks commonly known as evaporites. Evaporites include ; halite, anhydrite and gypsum. Gypsum has a density of 2.03 g/cc and chemical formula of a common mineral of evaporites ($CaSO_4 2H_2O$).
Halite	An evaporites rock also known as rock salt (NACL), with a density of 2.16 g/cc. Not sutable as acasing seat.
Limestone	A bedded sedimentary deposit consisting cheifly of calcium carbonate (CaCO3). Limestone is the most important and widely distributed of carbonate rocks and is the conslidated equivalent of limey muds, calcareous sand or shell fragments.
Sandstone	A cemented, or otherwise compacted, detrital sediment composed predominantly of quartz grains (SiO2), with a density of 2.65 g/cc.
Shale	A laminated sediments in which the constituent particles are predominantly of caly grade and with a density of 2.2 -2.8 g/cc.
Silt	A clasitic sediment, most of the particles of which are between 1/16 and 1/256 mm in diameter.
Anhydrite	This usually occurs as a massive mineral in evaporite beds. Anhydrite is usually very hard rock which while drilling, the rate of penetration (ROP) is low and acts as a cap rock. This is an excellent casing seat. Anhydrous calcium sulphate (CaSo4), with a density of 2.96 g/cc.
Chalk	Most likely, the softest rock that can be encountered in drilling operations, with a density of 2.71 g/cc. is is composed of the sheclls of floating microorganisms.
Chert	A very hard and abrasive siliceous rock usually formed precipitated silica (SiO2),but can also be of organic or precipitated origin. Chert usually cause massive drilling-string vibrations and the practice is to drill the entire section and set casing below it. Density of 2.65 g/cc.
Clay	Calys are formed from fine sediments with a particles size less than 1/256 mm in diameter. There are many varieties of clays ranging from totally inert to totally reactive in contact with water and from soft to very hard. Shale is the common name for clays and it indicates the rock has a structure:, e.g., bedding planes. Hence, some hard clays act as excellent casing seats, but the majority are probably unsuitable.
Conglomerate	Formed from water-eroded fragments of rock or pebbles. The fragments are usually rounded and are cemented together by another mineral substance. The hardness varies

from rock to rock and is controlled by the hardness of cementing rock. It can be an excellent casing seat and can also cause drill-string vibrations.

Flow Chart of Model's developments of (CCA)

Table - 4: Formation tops and lithology

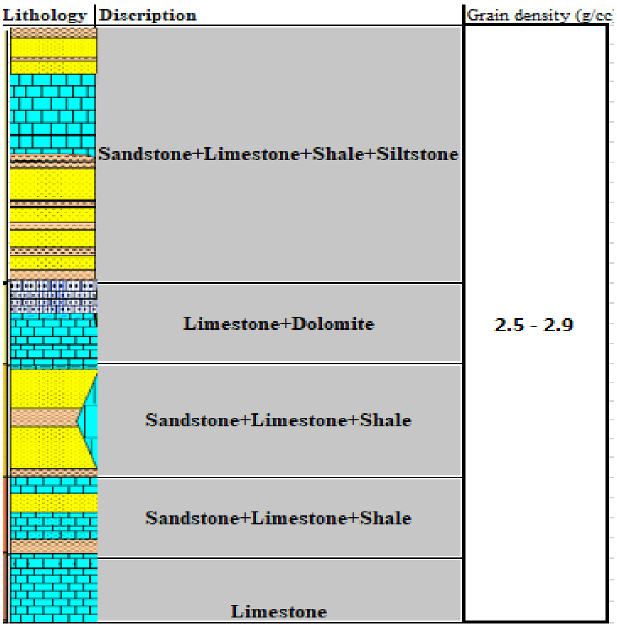

Table 5: Wellbore and drilled cutting properties.

Parameter	Value
Formation lithology type	Sandstone, limestone, and shale
Formation Temperature	(140 - 155) °F
Formation Porosity	0.15 - 0.25
Washout	0.1 -0.3
Drilling cuttings density	(20 - 24) pound per gallon (ppg)
Drilling cutting Size	(0.15 - 0. 3) inches (in)

Table 6: The drilling fluid characteristics.

Parameter	Characteristic Range
Oil ratio	(0.75 - 0.8)
Water ratio	(0.2 - 0.25)
Electrical stability	(400 - 600) Volts
low gravity solids	(2.5 - 5) Percent (%)
High gravity solids	(10 - 15) Percent (%)
March funnel viscosity	(65 - 75) second (sec)
Solid contents	(15) Percent (%)
Mud solid control equipment efficiency	0.5

Table - 7: Composition of the BHA considered to drill the sections.

Number of joints	Component	OD (in)	ID (in)	Weight (lb/ft)	Connection	Length (ft)
1	12.25 PDC drilling bit	8.5	2.78	120	pin 6-5/8 REG	0.89
1	RSS + Motor	6	5.25	105	Box 6-5/8 REG	35.4
1	Bottom sleeve stabilizer	6.125	-	-	Box 6-5/8 REG	35.4
1	Float Sub	6	3	127	Box 6-5/8 REG	2.82
1	String Stabilizer	6.25	3	127	Box 6-5/8 REG	7.24
1	Measurements While Drilling (MWD)	6.25	3.25	123	Box 6-5/8 REG	31.0
1	Downhole Screen HOS	6.25	3.25	123	Box 6-5/8 REG	6.20
4	Drill Spiral collar	6.25	3	127	Box 6-5/8 REG	120.2
1	Drilling jar	6.12	2.75	102	Box 6-5/8 REG	21.8
2	Drill Spiral collar	6.25	3	127	Box 6-5/8 REG	89.7
1	Cross-Over	6.25	3	127	Box 4-1/2 REG	2.89
5	Heavy Weight drill pipe (HWDP)	5.5	3	49.3	-	150.3
					Total	503.73

Table - 8: Abbreviations.

Items	Terms	Parameters	Acronyms	Unit
1	Pumping Rate	Drilling	GPM	Gal/min
2	Rate Of Penetration	Drilling	ROP	ft/hr
3	Open hole diameter or Bit size	Drilling	OH	in
4	Outer drill pipe diameter	Drilling	OD	in
5	Revolution per gal for motor	Drilling	rev/gal	rev/min
6	Hole section angel	Drilling	HA	deg
7	Drill string Rotation	Drilling	RPM	rev/min
8	Mud Weight	Rheology	MW	PCF
9	600 Viscometer reading	Rheology	R-600	CP
10	300 Viscometer reading	Rheology	R-300	CP
11	6 Viscometer reading	Rheology	R-6	CP
12	3 Viscometer reading	Rheology	R-3	CP
13	Developed Flow behavior index	Rheology	nm	CP
14	Developed Consistency Index	Rheology	km	CP

15	Developed Apparent viscosity	Rheology	M	CP
16	Cuttings Slip velocity for laminar flow	Hydraulic	Vsl	ft/min
17	Cuttings Slip velocity for turbulent flow	Hydraulic	Vst	ft/min
18	Cuttings rise velocity	Hydraulic	Vcr	ft/min
19	Cuttings transport velocity by gravitational force	Hydraulic	Vct	ft/min
20	modified Average Annular Velocity	Hydraulic	Va	ft/min
21	Cutting Concentration in Annulus	Hole Cleaning Indicator	CCA	%
22	Effective mud weight	Hydraulic	EMW	PCF
23	Equivalent cuttings weight	Drilling	ECW	PCF
24	Equivalent circulating density	Hydraulic	ECD	PCF
25	Average cuttings size	Drilling	dc	in

Equations

1. $Vcr = \frac{60}{\left(1-\left(\frac{OD}{OH}\right)^2\right)(0.64+\frac{18.2}{ROP})} cos(HA) + \frac{60}{\left(1-\left(\frac{OD}{OH}\right)^2\right)(0.64+\frac{18.2}{ROP})} sin(HA)$

2. $Vct =$

$$55 \left(\frac{22.5 - \left(\frac{MW}{7.481}\right)}{\left(\frac{MW}{7.481}\right)} (32.2)^3 \left(\frac{OH-OD}{12}\right)^3 \right)^{\frac{1}{6}} \cos(HA) +$$

$$55 \left(\frac{22.5 - \left(\frac{MW}{7.481}\right)}{\left(\frac{MW}{7.481}\right)} (32.2)^3 \left(\frac{OH-OD}{12}\right)^3 \right)^{\frac{1}{6}} \sin(HA)$$

3. $dc = 0.2 \left(\frac{ROP}{RPM+\frac{rev}{gal}GPM} \right)$

4. $Vst =$

$$113.4 \sqrt{\frac{0.2\left(\frac{ROP}{RPM+\frac{rev}{gal}GPM}\right)\left(22.5-\left(\frac{MW}{7.481}\right)\right)}{1.5\left(\frac{MW}{7.481}\right)}} \cos(HA) +$$

$$86.5 \sqrt{0.2\left(\frac{ROP}{RPM+\frac{rev}{gal}GPM}\right)\left(\frac{22.5}{\left(\frac{MW}{7.481}\right)} - 1\right)} \sin(HA)$$

5. $Va = Vst\cos(HA) + \frac{Vcr+Vct}{2}\sin(HA)$

6. $nm = 3.32\log,(\frac{((\mathrm{R600}-((2\mathrm{xR3})-\mathrm{R6}))}{((\mathrm{R300}-((2\mathrm{x\,R3})-\mathrm{R6}))}, Km = \frac{((\mathrm{R300}-((2\mathrm{x\,R3})-\mathrm{R6}))}{510^{n}}$

7. $\mu\mathrm{m} = \left(\frac{2.4(Va)}{OH-OD}\left(\frac{2nm+1}{3\,nm}\right)\right)^{n}(\frac{200\,Km(OH-OD)}{Va})$

8. $Vsl =$

$$\left(\frac{175\left(0.2\frac{\mathrm{ROP}}{\mathrm{RPM}+\frac{\mathrm{rev}}{\mathrm{gal}}\mathrm{GPM}}\right)\left(22.5-\frac{\mathrm{MW}}{7.481}\right)^{\mathrm{n}}}{\left(\frac{\mathrm{MW}}{7.481}\right)^{0.5\mathrm{nm}}\mu^{0.5\mathrm{nm}}}\right)\cos(HA) + \left(\frac{175\left(0.2\frac{\mathrm{ROP}}{\mathrm{RPM}+\frac{\mathrm{rev}}{\mathrm{gal}}\mathrm{GPM}}\right)\left(22.5-\frac{\mathrm{MW}}{7.481}\right)^{\mathrm{nm}}}{\left(\frac{\mathrm{MW}}{7.481}\right)^{0.5\mathrm{nm}}\mu^{0.5\mathrm{nm}}}\right)\sin(HA)$$

9. $CCA = \frac{ROP\,OH^{2}}{60\,(Va-\frac{Vsl+Vst}{2})(OH^{2}-OD^{2})}$

10. $EMW = MW(CCA) + ME, \quad ECW = MW(CCA) + MW + (1-CCA)MW$

11. $ECD = EMW + 7.481(\frac{0.1}{OH-OD}((2R300-(2R3-R6))-(R600-(2R3-R6)) + \frac{((R600-(2R3-R6))-(R300-(2R3-R6)))\,Va}{300(OH-OD)})$

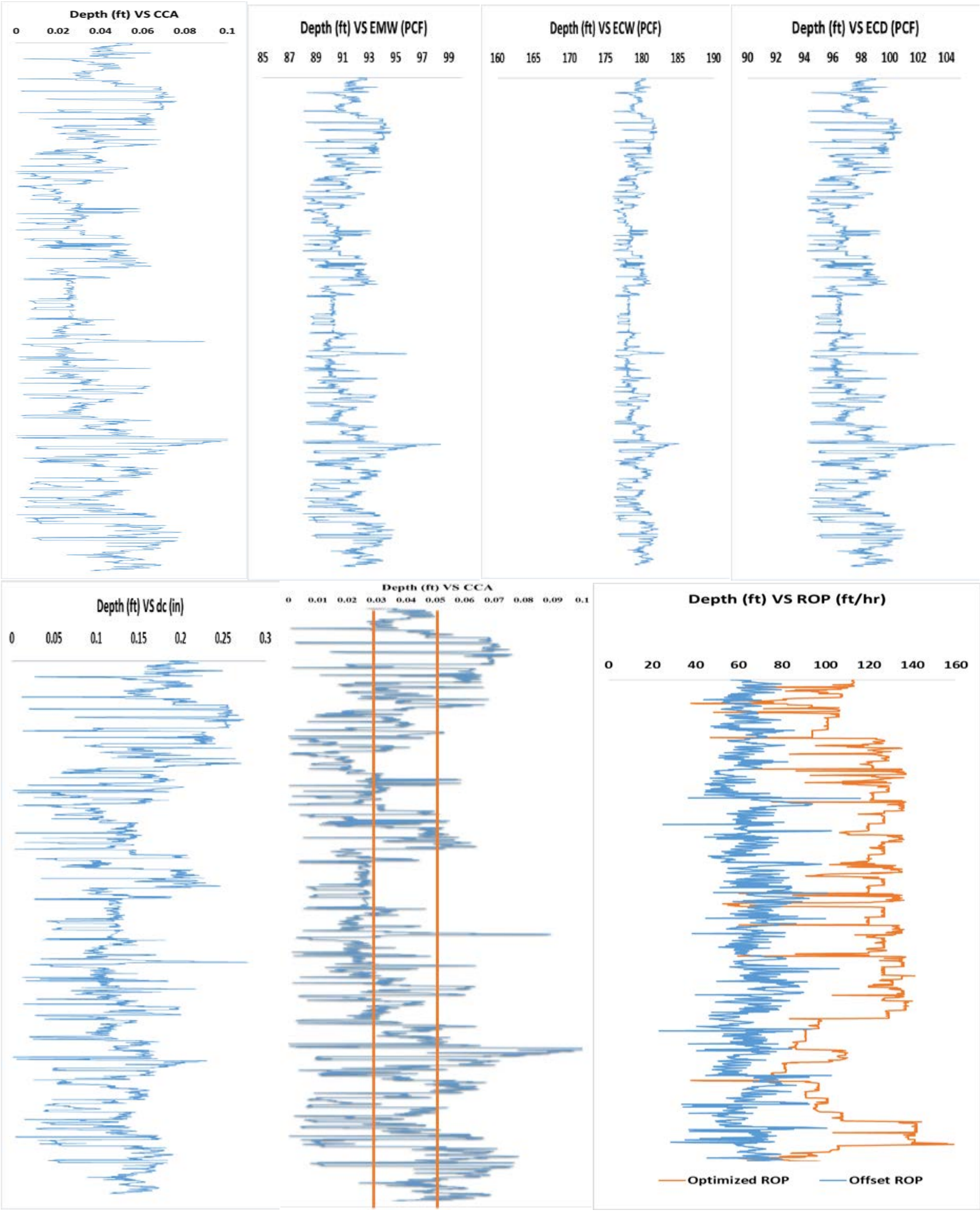

Figure 1. Depth vs cutting concentration, EMW, ECW, ECD, offset and optimized ROP.