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Full Length Research Paper

Evaluation of reservoir depletion degree using equivalent mud weight window log of a Norwegian oil reservoir

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Abstract

In the late 20th century, reports of unsuccessful development and production of drilled wellbore and inaccurate estimation of proven and portable oil reserve were of concern to the petroleum industry. Consequently, research has focused on the evaluation of reservoir depletion degree on solution gas drive. But, most of these studies were conducted experimentally at simulated reservoir conditions. Few of these studies were conducted real-time using live data under reservoir prevailing conditions while drilling or producing. Moreover, data of equivalent mud weight (EMW) window logs were not investigated toward the prediction of reservoir depletion degree. Consequently, this paper used an EMW Window log of a single well of a Norwegian continental shelf oil reservoir located at the SST oilfield as a case study, to evaluate the depletion degree of the oil reservoir. The case study employed theoretical and analytical approaches to develop a model. The resulting model was used with the predicted reservoir depletion degree from the EMW window log and oil production performance log to establish a new method of reservoir depletion evaluation. These were achieved using Microsoft Excel 2010 and IBM SPSS as the data analysis tools. The results obtained from the model show that the reservoir depletion was at an average degree of 0.03% with an average pressure drawdown of 147 psi at the drilling stage, while at the oil production stage the reservoir depletion was at an average degree of 0.81% with an average pressure drawdown of 156 psi. The evaluated reservoir depletion degrees proportional relationship show that 27% of the proven oil reserve was recovered in the oil reservoir. These results evidenced that there exists a direct proportional relationship between the equivalent mud weight and pore pressure, while the reservoir depletion is inversely proportional to the pore pressure in an oil reservoir undergoing solution gas drive. This research demonstrates that the use of equivalent mud weight in the evaluation of reservoir depletion degree would lead to a multi-disciplinary approach to reservoir characterisation and management that would maximize oil recovery and improve the design of upstream oil and gas surface equipment.

Keywords: Equivalent Mud Weight, Pore Pressure, Reservoir Depletion Degree, and Solution Gas Drive.

1.0 INTRODUCTION

In the second-half of the 20th century, real-time evaluation of reservoir depletion degree at reservoir prevailing conditions has advanced considerably in the exploration and production sector of the petroleum industry. These advances have been in regard to frequent reported unsuccessful development and production activities. These have been evidenced due to poor evaluation of reservoir depletion degree on reservoir undergoing solution gas drive while drilling. Consequently, over the years research has focused on the evaluation of reservoir depletion degree on solution gas drive. Most of these studies were conducted experimentally with glass-micro model units, at simulated reservoir conditions (Daneshet al. 1987, and Pooladi-Darvish and Firoozabadi1999). Only one study used measured data from logging-while-drilling (Fangming *et al.* 2009). Fangming *et al.* (2009) used measuring data collected from logging-while-drilling (LWD) log of a horizontal well, and it was observed that depletion occurred when the initial reservoir pressure of 1740 psi dropped below the bubble point pressure (1595 psi) to about 1319 psi. The empirical model which evaluated the reservoir depletion degree were close to the modular formation dynamic tester (MDT) and gas-to-oil ratio with a relative error of 7.5% and 10.5% respectively. Fangming *et al.* also recommended that, the method was not applicable to mud filtrate invaded reservoir. However, most of these previous studies were not conducted at reservoir prevailing conditions. Moreover, Pooladi-Darvish and Firoozabadi proved that, high rate of reservoir depletion below the bubble point pressure does not immediately produce gas-to-oil ratio (GOR); rather it mobilized crude oil to the wellbore due to gas bubble dispersion in the flow. Similarly, Islam and Chakma (1990), and Sarma and Maini (1992) in an earlier separated studies affirmed the theorem that when reservoir pressure depletes below the reservoir bubble point pressure to an extent, the gas bubbles coalesce and form a continue-flow-phase. The flow becomes two-phase flow of oil and gas through the reservoir formation pores of the reservoir to the wellbore, producing GOR. In addition, Jones *et al.* (1999) affirmed that at high pressure drawdown, there exist subsequent gas bubble nucleation, growth and coalescing. Finally, the glass micro models used in the experiments did not represent the reservoir real conditions and cannot be replicated, but aided to visualise the predicted pseudo-depletion rate. Conversely, Fangming *et al.* study was not only validated by scientific methods, but involved real-time (neutron and density porosity log, and formation pressure) data at the reservoir prevailing conditions. In contrast, Fangming *et al.* research was only feasible to none mud invaded wellbore of oil reservoirs, and the exclusion of EMW window log in the prediction of reservoir depletion degree. The recommendation for the inclusion of EMW log in evaluating reservoir depletion degrees is the underpinning research gap that stirred this study. Conceptually, figure 1.1 depicts that label 6 has not been used by previous studies to evaluate the degree of reservoir depletion.

Therefore, this paper is aimed at evaluating reservoir depletion degree from an EMW window log obtained while drilling. The result obtained will be used to generate a propositional relationship with the evaluated reservoir depletion degree obtained from the oil production performance data logs of the same well, and benchmarked with the solution gas drive ultimate oil recovery limit. This was achieved by the underpinned objectives: to examine the various quantity of EMW applied at the critical measuring depths, and to estimate the wellbore pore pressure at these various measuring depth using EMWs; to evaluate the degree of reservoir depletion from the estimated wellbore pore pressure from the EMW window log; to estimate the reservoir depletion degree from the oil production performance log; and to justify the proportional relationship between the two evaluated depletion degrees, and recommend a correlation between the evaluated degrees of reservoir depletion by benchmarking it with the solution gas drive ultimate oil recovery limit. These logs used were collected from a single wellbore located in the Norwegian continental shelf at SST Oilfield.

2.0 Study Area

SST oilfield is located offshore in the Norwegian continental shelf at a water depth of 260 metres, and was discovered in May, 2009 by horizontal appraisal well. The oilfield started production by depletion (solution gas drive) in 1st January, 2010. An accumulative stock tank barrel of 90 bbl./month of oil was produced on the 1st of February, 2010. The contents of oil produced were without water and producing GOR. In addition, prior to production the reservoir's proven and portable oil reserve was estimated to be 20,830,132.00 bbl. The reservoir is expected to be in production up to 1st July, 2018. The reservoir was a saturated oil reservoir. The initial reservoir and the bubble point pressures were approximately estimated as 5,509 psi and 2,600 psi respectively, and the initial reservoir temperature was about 98^{o}F but is producing isothermally at 60^{o}F. The oil reservoir is characterised as ordinary black oil with an initial producing GOR of 250 scf/STB, high density of 18.6 ^{o}API, high viscosity of 12cp and sulphur content of 0.82%. The reservoir has no initial gas cap.

The reservoir hydrocarbon fluid is found in the heimdal and sandstone formations. The formations are laminated in-between by shale, and the reservoir cap rock is clay stone. The oil reservoir occupies an area of 10 km², and has an average pay thickness of 47.7m. The formation porosity ranges from 6% to 39% with a mean porosity of 33%, while the formation permeability ranges from 5-10 Darcies with a mean permeability of 7 Darcies.

3.0 METHODOLOGY

3.1 Method

A combination of analytical and theoretical case study were undertaken to evaluate the degree of reservoir depletion using log of equivalent mud weight window. The study further evaluated another degree of reservoir depletion from the oil production performance data. Both evaluated

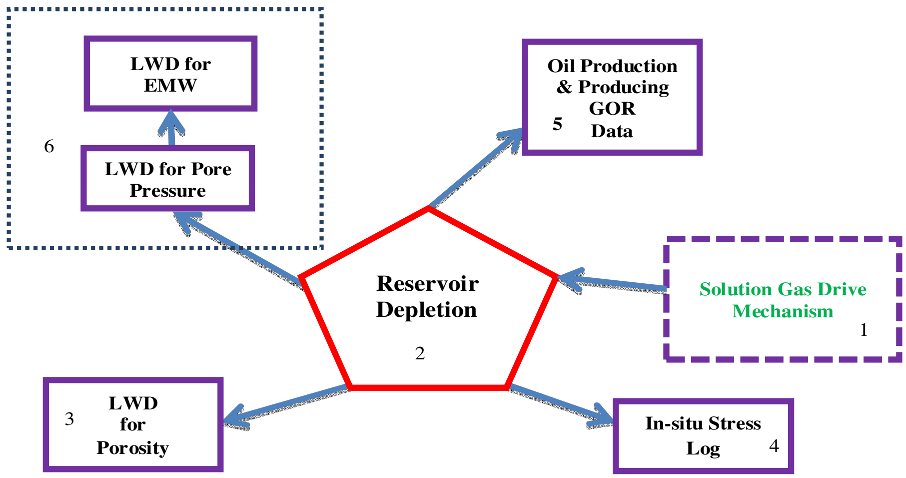


Figure 1.1: Conceptualised pentagonal diagram illustrating the possible logs of oil Reservoir undergoing depletion by solution gas drive, and the research gap of this study

depletion degrees were used to develop a proportional relationship by benchmarking it with the solution gas drive ultimate oil recovery limit of a saturated reservoir to a certain the model. In addition, this study also adopted a conceptualised flow-chart to illustrate the sequence of data collection, computation and analysis. The conceptualised flow-chart illustrates the procedures used in the case study model. The investigating unit of the case study was identified as the reservoir depletion, and the quantitative secondary data were gathered to study and understand the application of the methods, the data were sourced from a single well (SST) located in a Norwegian reservoir offshore and were originally collected from a real-time measuring devices.

3.2 Data Extraction Technique and Formulae Used

The quantitative secondary data gathered were equivalent mud weight window and oil production performance logs. These logs were collected in two forms: graph and tabulated numerals. To have a homogenous set of data, both data were extracted, refined and presented in numeric form. In addition, the obtained numeral units were converted from Norwegian field units to British imperial units. These refined data were used as inputs in the outlined formulae to extract the required data following the procedures, which lead to the achievement of the targeted aim of this study.

3.2.1 Phase I: Formulae and Procedures used for the Evaluation of Reservoir Depletion Degree from the Equivalent Mud Weight Window Log

In this phase, data about EMWs application on pore pressure at specified critical measuring depths were examined and estimated. These procedures used are outlined as stated below:

3.2.1.1 Prediction of Pore Pressure from EMW Window Log

Technically, equivalent mud weights were increased intermittently during drilling to cope with the rate at which pore pressure is naturally increased intermittently. This indicator was widely evidenced in various studies as pore pressure gradients (Bourgoyne *et al.* 1986 and Azar and Samuel 2007). On this premise, the following equations were employed.

i Pore Pressure Gradient (psi/ft.) = 0.052 * Equivalent Mud Weigh

P_{Rg} (psi/ft.) = 0.052 * EMW … 3.1 (Bourgoyne *et al.* 1986)

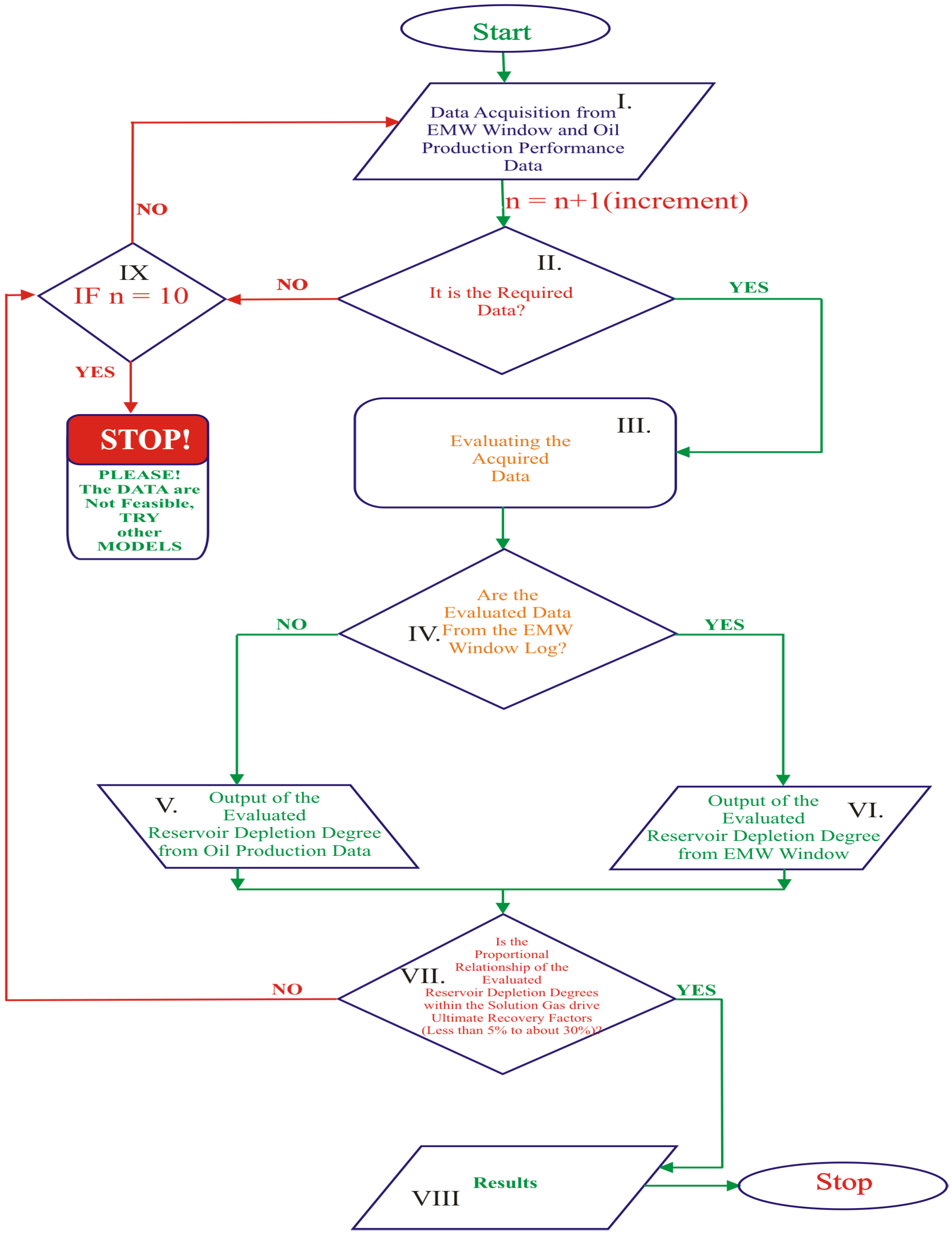
ii Pore pressure (psi) = Pore pressure gradient * Total vertical Depth

P_R (psi) = P_{Rg} * MD … 3.2 (Bourgoyne *et al.* 1986)

iii The rate of EMWs application

EMW_r (%) = $\frac{D_e}{D_b}$ ….. 3.3

iv The rate of change (ROC) EMW due to pore pressure change



Where n = is the counter and the duration of data collection and analysis

Figure 3.1: Conceptualised model illustrating the methodological algorithms for predicting reservoir depletion degree for an oil reservoir.

v $EMW_c\,(\%) = \frac{D_e}{D_b} - 1$ ….. 3.4

3.2.1.2 Evaluation of Reservoir Depletion Degree using the Evaluated Pore Pressure of the EMW Window Log

The most appropriate relationship to describe reservoir depletion response will be subject to how it reacts inversely to changes in pore pressure

vi Then the reciprocals of the pore pressure, P_R (psi) at intermediate MD just after the cap rock would be evaluated to estimate the reservoir depletion, R_w (psi)

$$R_w \text{ (psi)} = \frac{1}{P_R} \quad \ldots \quad 3.5$$

vii The mean rate of reservoir depletion from the EMW Window Log

$$\text{Mean } R_w\ (\%) = \frac{D_e}{D_b} \quad \ldots \quad 3.6$$

3.2.2 Phase II: Formulae and Procedures Employed for the Evaluation of Reservoir depletion degree of the Oil Production Performance Log.

It has been established that rate of reservoir depletion can be described in terms of pore pressure changes. In this phase, data of the oil production performance log were used to evaluate the reservoir depletion degree (R_r) and average depletion degree (mean R_r) .

3.2.2.1 Collection of Depletion rate data from oil Production Performance Log

The data for the evaluation of reservoir depletion from the oil production performance data was examined, extracted, tabulated and computed for the duration of 0 to 3 years. These data were also used to evaluate the reservoir depletion degree and the mean reservoir depletion degree (R_d) using the depletion rate equation (see equation 3.7).

viii The rate of depletion from the oil production performance Log

$$R_r(\%) = \frac{R_{ror}}{q_t} = \frac{R_{ior} - Q_t}{q_t} \quad \ldots \quad 3.7$$

(Höök 2009: 33)

ix The mean rate of depletion from the oil production performance Log

$$\text{Mean } R_r(\%) = \frac{R_e}{R_b} \quad \ldots \quad 3.8$$

3.2.3 Phase III: Formulae and Procedures used to justify the Proportional Relationship between Phases I and II

3.2.3.1 Estimating the Proportional Relationship between the Results Obtained in Phases I and II

The oil recovery factor of the solution gas drive mechanism was used to establish the proportional relationship the evaluated degrees of depletion from the equivalent mud weight window log and the oil production performance log. This was conducted using the ultimate recovery of solution gas drive limit between less than 5% to about 30% as the benchmark.

3.3 Data Analysis

In this work, the data were analysed with multivariate statistics and regression tool in IBM SPSS Statistics and spreadsheet tool in Microsoft Excel 2010. Also the analysis was conducted on the relationship between: (i.) EMW against P_R, (ii.) EMW and P_R against TVD, (iii.)EMWr and EMWc against P_R, (iv) P_R and R_W, (v) average daily oil rate production and time, (vi) FBHP against average monthly oil production rate, and (vii) Reservoir depletion and monthly oil production rate against time. Moreover, in cause of these analyses formulae were generated and used in the evaluation of the degree of reservoir depletion. In a similar research Fangming, *et al*. (2009) used formulae to extract data from LWD logs, and these data were analysed with multivariate statistics and regression tool to generate correlations that enabled the prediction of the reservoir depletion degree. Hence, the method of data analysis adopted in this study is suitable and up-to-date.

4.0 RESULTS AND DISCUSSION

4.1 The Examined Quantities of EMWs Applied at the Critical Measuring Depths, and the Estimated Wellbore Pore Pressure at These Measuring Depths obtained from the Equivalent Mud Weight (EMW) Window Log

4.1.1 Predicted EMWs Applied at the Critical Measuring Depths and the associated Wellbore Pore Pressures due to Reservoir Depletion

The relationship between the equivalent mud weight and wellbore pore pressure has been justified on the scatter plot diagram as shown on figure 4.1, and the regression output analysis were presented in table A1.1 in appendix 1. The justification was conducted on IBM SPSS statistics regression analysis tool. This was aimed to ascertain if the data extracted from the EMW window log were significant to the model. Subsequently, the outcomes of the analysis were evaluated at 95% confidence level, and the results obtained indicated that the significance factor and R-square were at 0.012 and 0.910, respectively. Similar procedure was also evidenced in Majdi*et al.* (2010) research.

The significance factor estimated was less than 0.05, which implies that the relationship are significance and acceptable to the model. Furthermore, the estimated R-square of 91% suggested that, 91% of the EMW can be

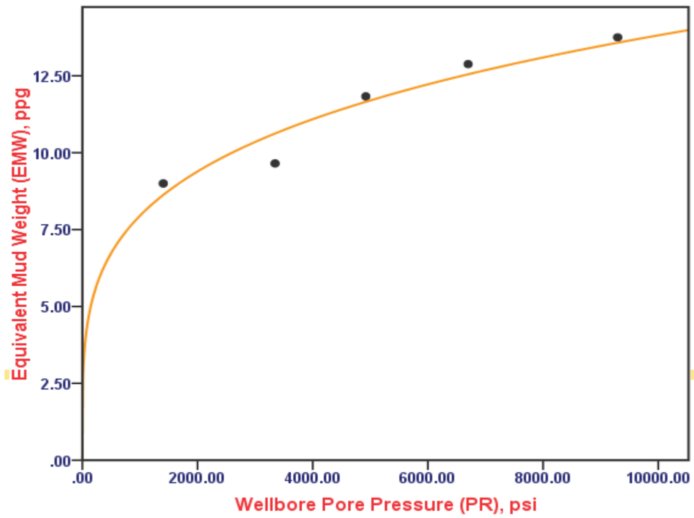


Figure 4.1: Relationship between equivalent mud weight and Wellbore pore pressure on the equivalent mud weight window log while drilling.

explained by P_R; based on this premise figure 4.1 shows that there is a statistical power relationship between EMW and P_R when the SST4 wellbore was drilled. The relationship between EMW and P_R as depicted on figure 4.1 is mathematically expressed as by equation

4.1. This equation was obtained from the regression analysis.

$$\mathrm{EMW} = 1.516 * \mathrm{P}_{\mathrm{R}}^{0.240} \qquad \ldots \qquad 4.1$$

This suggested that the EMW was directly proportional to the wellbore pore pressure, and intrinsically a function of depth. From equation 4.1, the EMW is the dependent variable that was used to keep the wellbore independent variable, P_R in-place. Simultaneously, when the in-situ independent variable of the reservoir P_R increased by 1 psi the EMW was increased by 1.52 ppg while the wellbore was drilled. The equation also shows that the constant coefficient 1.516 represents the uncertainties that may impede pore pressure flow due to reservoir depletion. The major impedance identified were the alterations of formation porosity and permeability configuration. These alterations caused were due to some immediate factors identified such as in-situ stress and skin effect, while the root cause was attributed to the reservoir depletion degree.

Therefore, continues intermittent natural increase of pore pressure in wellbore while drilling also influenced the intermittent increase of the EMW. The increment of EMW was aimed to drill a successful and stabilised wellbore to the targeted pay zone. This evidence affirms Jackson and Heysse (1994) argument that, EMW are increased to sustain wellbore stability during drilling.

In addition, figure 4.2 illustrates that when the compaction of the reservoir section was penetrated by the drill bit, the pressure was 1404 psi and an EMW of 9 ppg was applied to stabilise the wellbore to enable drilling activities at measuring depth (MD) of about 3000 ft. Similarly at another MD the flowing bottom-hole pressure (FBHP) was observed to be 9295 psi, while the mud equivalent mud weight used to keep it in place was 13.75 ppg at MD of 13000 ft. It was obviously depicted on figure 4.2 and expressed mathematically, that throughout the drilling cycle, the mud weight was higher than the P_R with an average pore pressure of about 147 psi. However the mud weights were marginally higher than P_R between the pore pressures ranges of 1404 psi to 4921 psi, and about 5000 psi to 9295 psi respectively, due to the heterogeneous compactions experienced. These observations had the same underpinned explanation opined by an early scholar Badri *et al.* (2001). Frequency curve analyses were conducted on the EMW dataset. The results obtained were expressed in terms of the rate and rate of change. The rate and rate of change of EMW application on P_R are presented in figure 4.3, and output of the frequency curve analysis are presented in appendix 2. The results suggested that the EMW application on the P_R while drilling had an average rate (EMW_r) and rate of change (EMW_c) of 89.20% and 9.20% respectively. In addition, figure 4.3 also suggests that the wellbore experienced high pressures mostly between the measuring depths of 8000 ft. to 12000 ft. However, both the mean EMW_r and EMW_c declined within the pay zone and were about to maintain a plateau. This evidenced that the equivalent mud weights were about being in equilibrium

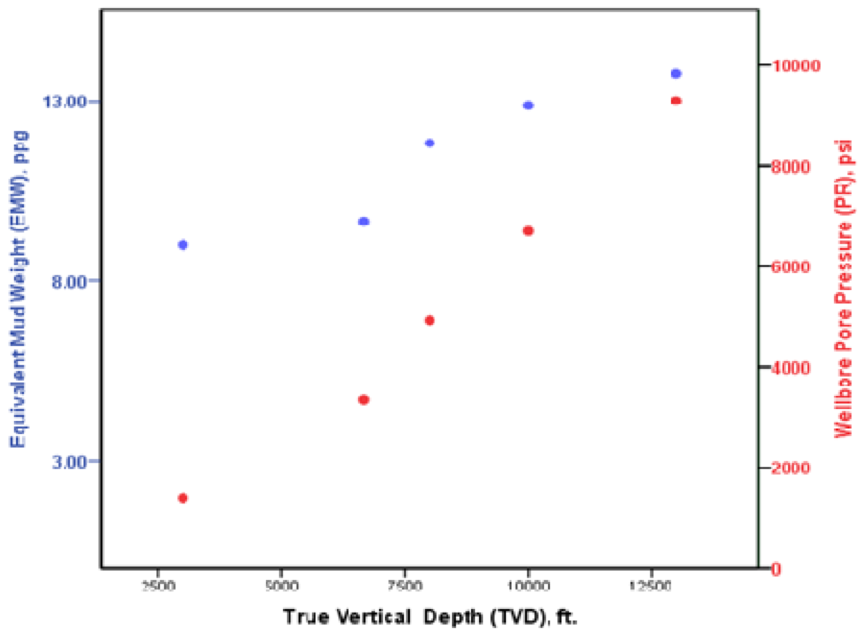


Figure 4.2: The trajectory of EMW and PR while drilling at various measuring depths.

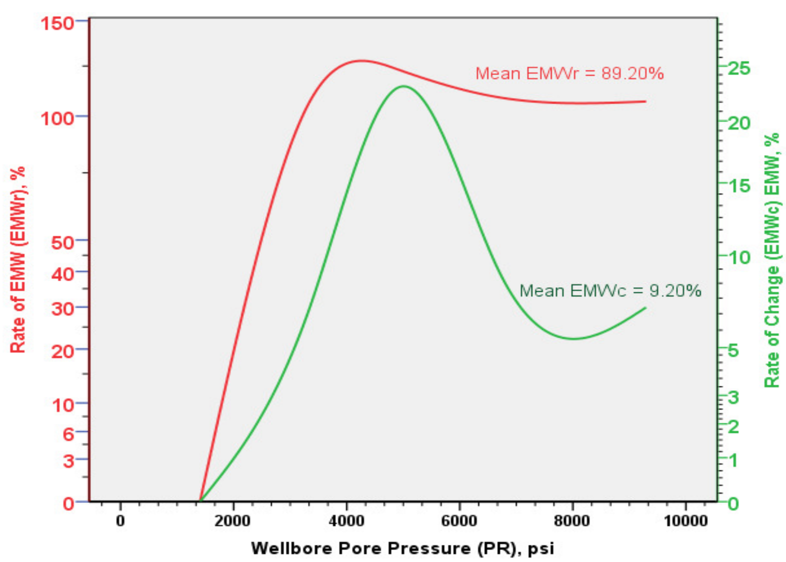


Figure 4.3: Relationship between equivalent mud weight's rates and rate of changes applied on the pore pressure while drilling.

state with the reservoir build up pressure. The build up pressure is a product of the absolution of the dissolved gas in the hydrocarbon liquid. A similar situation was also appraised and examined by Pattillo, Cocales, and Morey (2006) that the high pressure experienced in an open hole are due to pressure build up which is associated with gas expansion in crude oil. Moreover, Hemphill (2012) explain that the most hazardous period of drilling a wellbore is during pressure build up. Hemphill illustrated this concept on a safe drilling window. However, Pattillo, Cocales, and

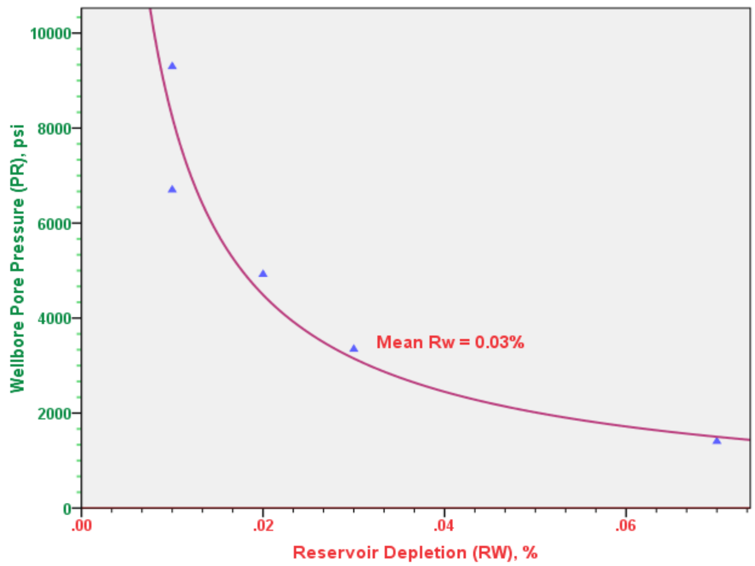


Figure 4.4: Relationship between the wellbore pore pressure and Reservoir depletion experienced in the wellbore.

Morey and Hemphill did not employ the EMW_r and EMW_c parameters in discussing the claims.

4.2 The Evaluated Degree of Reservoir Depletion Derived from the Estimated Wellbore Pore Pressure from the Equivalent Mud Weight (EMW) Window Log

4.2.1 The Evaluated Reservoir Depletion Degree from the Estimated Wellbore Pore Pressure

Figure 4.3 shows that mud weights were always increased intermittently by the mud Engineer, and these increments were aimed to keep the wellbore pore pressure in-place and to sustain wellbore stability while drilling. However, the result in figure 4.4 illustrates the relationship between the evaluated wellbore pore pressure and reservoir depletion. The study identified that the wellbore pore pressure was the medium at which the EMW received the impact of the reservoir depletion. This was observed at the stage of pressure build-up, mostly during the formation of a pseudo-secondary gas cap. This was also concluded by an early scholar, Wingen (1942).

Consequently, the relationship between the wellbore pore pressure and reservoir depletion were also examined and analysed with the multivariate statistical and regression tool. The results obtained are depicted and presented on the scatter plot diagram shown in figure 4.4. In addition, the regression analysis output was also presented on in appendix 3. The results obtained from the analysis were on the basis of 95% confidence level, while the R-square and the significance factor obtained from the analysis were 0.99 and 0.00037 respectively. These statistical results obtained interpreted that the variables were significant, acceptable and suitable to the model. Sequel to these analyses and results obtained from the model's summary and parameters, equation 4.2 was developed. The developed equation facilitated the prediction of the depletion degree experienced at the wellbore. The equation was expressed making the dependent variable (P_R) the subject of the formulae.

$$P_R = 146.59 * R_w^{-0.875} \quad \ldots \quad 4.2$$

Critically analyzing the result depicted in figure 4.4 and the developed equation in equation 4.2. Figure 4.4 illustrate that as drilling commenced in the reservoir section there was an instantaneous reservoir pressure drawdown. The instantaneous reservoir pressure drawdown was suggested to be due to the vibration and resonance effects attributed to the drill bits. As shown in Figure 4.4, the reservoir depletion commenced from higher to lower pressure. The reservoir depletion started at the estimated rate of 0.1% with the pressure of 9295 psi and the depletion kept increasing and terminated at 0.7% with the estimated pressure of 1404 psi. The estimated mean reservoir depletion degree was evaluated as 0.03%. Furthermore, from equation 4.2 it was observed that if 1% of depletion degree occurs the wellbore received the impact 147 psi pressure drawdown. On this premise, a similar observation was explained by Vogel (1968), however, when the wellbore was under production. Therefore, this has shown that reservoir depletion degree can be explained in terms of pore pressure changes even at the drilling stage. That is, in a saturated oil reservoir,

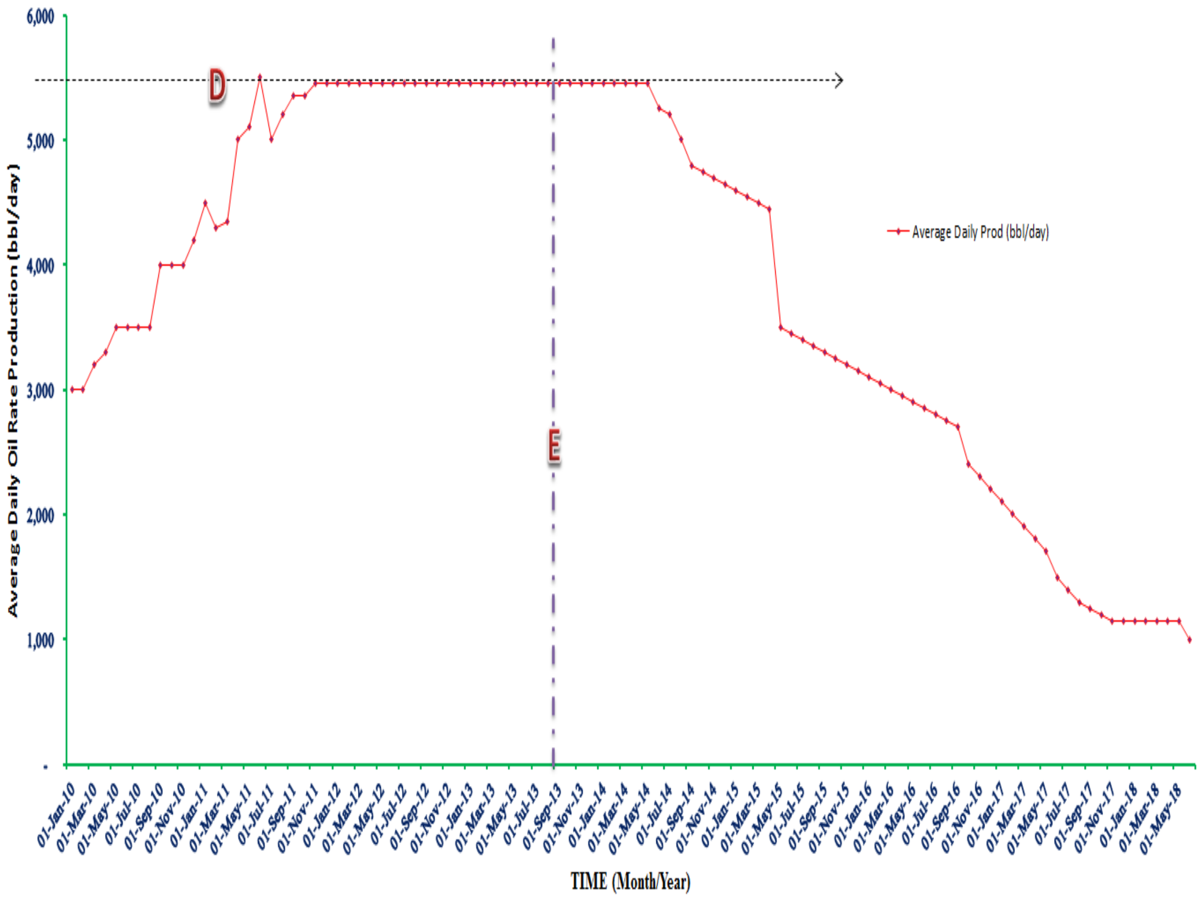


Figure 4.5: Monthly Oil rate production at the single well SST4 with solution gas drive mechanism for oil produced between January 2010 and September 2013

higher depletion degree corresponds with greater pore pressure decrease. This confirmed Vogel (1968) and Fangming *et al.* (2009) explanation on reservoir depletion in terms of pressure drawdown.

Therefore, equation 4.2 can be employed to evaluate reservoir depletion degree from the equivalent mud window log. However, the correlation between the estimated depletion degrees is discussed in section 4.3. The correlation is between estimated depletion degrees obtained from the EMW window log and the oil production performance data.

4.3 Estimated Reservoir Depletion Degree Obtained from the Oil Production Performance Log

4.3.1 Results from the Oil Production Performance Data

The results presented and discussed in this section were aimed at explicitly illustrating the correlation between the estimated depletion rates. The correlation would easily be used for forecasting depletion rate for similar oil reservoir. Consequently, year 0-3 oil production data log were used in the analysis to generate these results. These results were obtained on the basis that the proven and portable oil reserve was estimated as 20,834,134.00 bbl., and solution gas drive ultimate oil recovery is 30%. On this basis, these results presented herein were meant for oil produced between January 2010 and September 2013.

Figure 4.5 indicates that the daily oil production logs were encapsulated into a 30-day (monthly) report. This was done for the purposes of homogeneity and understanding of the result obtained. The result shows that oil production under solution gas drive mechanism curve, including its growths and declines stages. The growth oscillates due to formation conditions, political, economic, weather and equipment functionally, depletion rate, just to mention but few. However, these factors aforementioned except depletion rate were above the scope of the study. Hence, these factors were not discussed in the study except depletion rate. From figure 4.5 the depletion rate was the intrinsic factor that yields oil production. The oil rate production curve attained a plateau at level D. This shows that the oil rate was at equilibrium with the pressure drawdown.

Single Well SST4 at SST Oilfield Recovery Analysis		
	Oil	**Unit**
Proven and Portable Reserve	**20,830,132.00**	bbl
Solution Gas Drive Recovery Factor 30%	**6,249,039.60**	bbl
Unrecovered Theoretical Portable Reserve	**14,581,092.40**	bbl
Average Reservoir Depletion Degree (0 to 3 years)	**0.81%**	

Table 4.1: Breakdown on the oil recovery from the proven and portable Reserve undergone solution gas drive mechanism for oil produced between January 2010 and September 2013

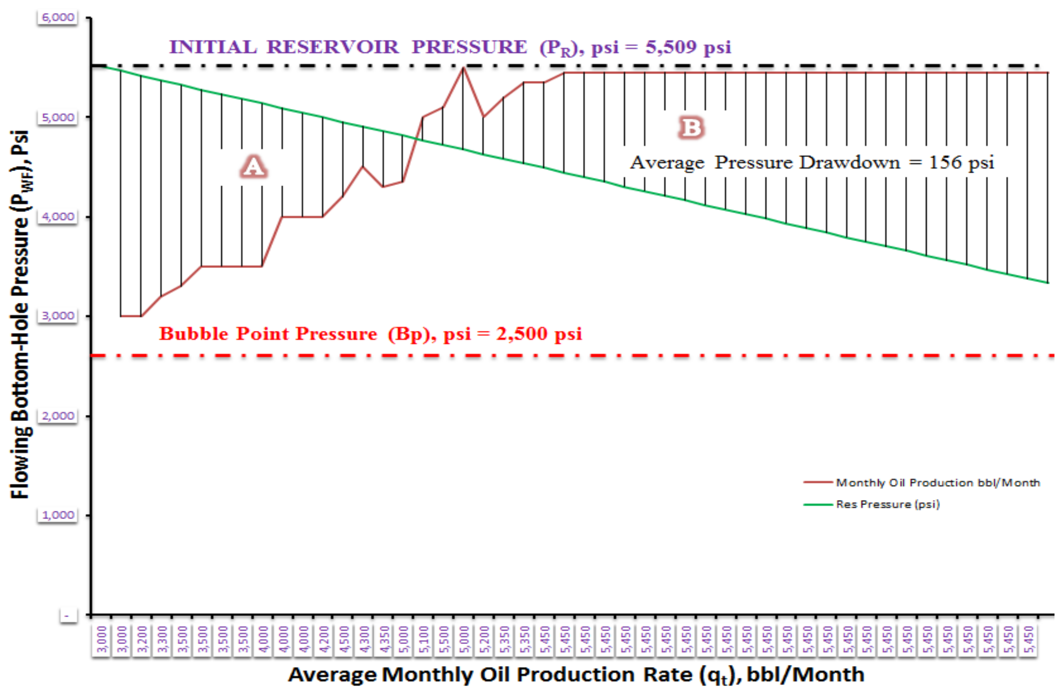


Figure 4.6: Flow pattern of oil at the SST4 wellbore bottom-hole as the reservoir pressure undergoes pressure drawdown

Furthermore, the result indicates that the solution gas drive mechanism ultimately oil recovery of 30% terminated at the intersection of line E. In terms of time, this took the oil production into 1st September, 2013. These are explicitly presented in table 4.1.

Figure 4.6 shows the oil production profile of the single SST4 wellbore at SST Oilfield located in the Norwegian continental shelf. The reservoir started production with an initial reservoir pressure (P_R) far above the reservoir bubble point pressure (B_p). The initial reservoir pressure was 5,509 psi while the reservoir bubble point pressure is 2600 psi. In addition, the figure, figure 4.6 illustrates that monthly oil production occurred at an average reservoir pressure drawdown of 156 psi. At section A, it was identified that as the reservoir pressure depleted (drawdown),that is the green line declines, correspondingly the rate of oil production grew (see red curve) and maintained a semi-plateau at section B, an attribute associated with oil reservoir. The result shown in figure 4.6 predicts that gas-oil ratio production was null within the duration. Since, the reservoir pressure was above the reservoir bubble point pressure.

Generally, the pressure drawdown can be obtained from the positive difference between the reservoir pressure and the flowing bottom-hole pressure (Vogel 1968 and Ahmed 2000). In addition the pressure drawdown can be described as the force per area that drives oil to the

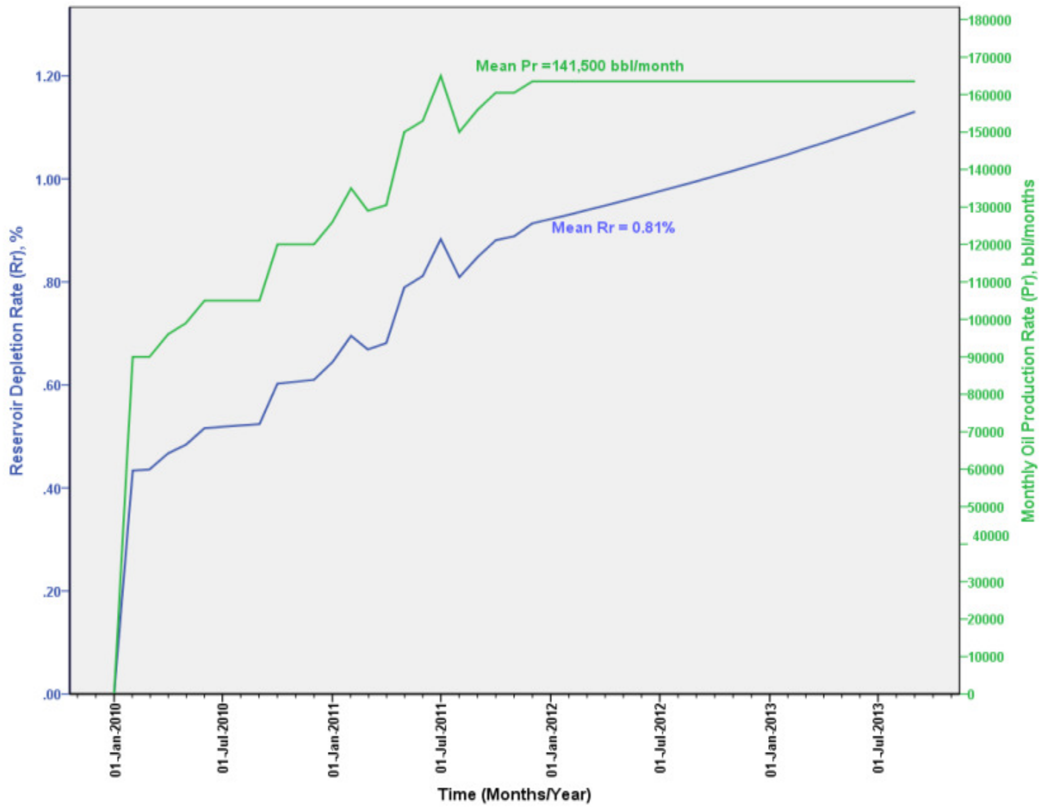


Figure 4.7: Mean monthly oil production rate and degree of reservoir depletion at the SST4 wellbore bottom-hole.

wellbore due to pressure potential difference. The result shows that, the reservoir was a saturated oil reservoir with solution gas drive. Nevertheless, it can be stated that reservoir depletion degree is inversely propositional to pressure drawdown (Vogel 1968). Similarly, as pressure drawdown occurs, hydrocarbon fluid depletes at different depletion rates at the prevailing reservoir conditions. Also, oil production at stock tank conditions produce at different rate, both with respect to time. On this basis, figure 4.7 was used to illustrate the different flow rates with respect to time.

Furthermore, from figure 4.7 it was also acknowledged that the mean depletion rate at the reservoir conditions and the mean oil production rate at stock tank Conditions were 0.81% and 141,500 bbl/month respectively.

4.4 The Proportional Relationship between the Two Evaluated Depletion Degrees.

4.4.1 Relationship between the Estimated Reservoir Depletion Degrees from Equivalent Mud Weight and Oil Production Performance Log

Figure 4.8 shows the results of the evaluated reservoir depletion degrees during drilling and production of the study. It was estimated that the evaluated depletion degree value (0.03%) of the EMW window log was significantly lower than the value (0.81%) obtained from the oil production data log. Notwithstanding, the broad variation between these results were normal in terms of wellbore oil production. Basically during drilling the from conductor zone to pay zone the hydrocarbon fluids were not allowed to flow upstream in the wellbore according to Azar and Samuel (2007), while Ahmed (2000) opined that hydrocarbon fluid flow through the wellbore during the production stage. Therefore, during drilling the wellbore conditions assumed the reservoir to be in conditions with a lower depletion rate due to pressure build up. At this point it is suggested that for an average depletion degree of 0.03% experienced by the EMW during drilling is approximately equal to an average depletion degree of 0.81% at the oil production stage. On the basis of this relationship, the recovery factor of the solution gas drive mechanism from the available results was 27%. The results obtained also show that the evaluated reservoir depletion degree while drilling and production were 0.03% at a pore pressure drawdown of 147 psi and 0.81% at a pressure drawdown of 156 psi respectively. This evidence

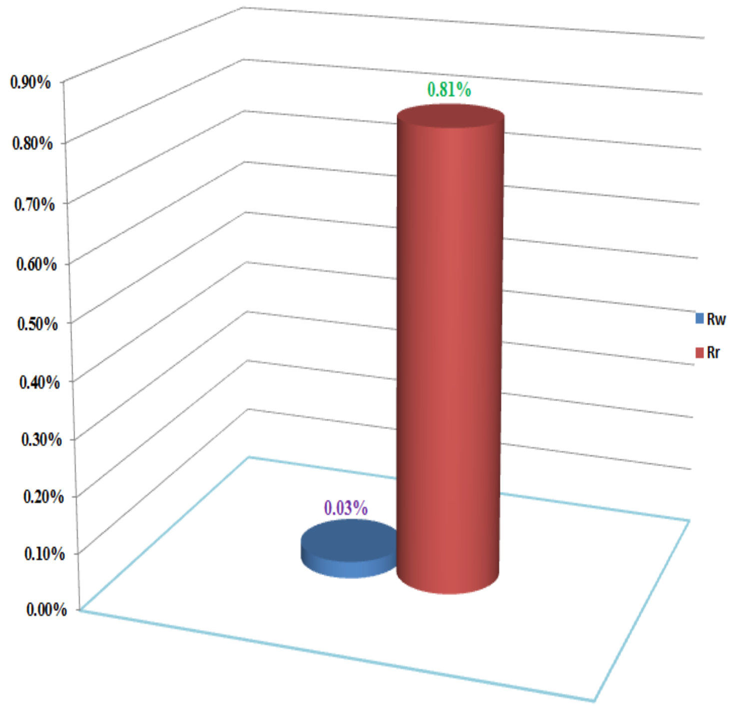


Figure 4.8: Evaluated reservoir depletion degrees experienced at the wellbore while drilling (R_W), and during oil production (R_r).

gives support to the findings of early researcher such as Teufel, Rhett, and Farrell (1991) and Valko´ and McCain (2008) and confirms Vogel (1968) explanation on reservoir pressure drawdown protocol.

5.0 CONCLUSION

- It was observed that at various measuring depths the naturally increased pore pressures due to relative reservoir depletion were keep in-place by different EMWs.
- The EMWs applied on the pore pressures were at the average rate (EMW_r) and average rate of change (EMW_c) of 89.20% and 9.20% respectively.
- The equivalent mud weights were directly proportional to the pore pressure when the well was drilled. The equivalent mud weight was slightly higher than the mud weight (over-balanced drilling) with a relative pressure of 147 psi which was insignificant. This accounted for the pressure drawdown.
- The equivalent mud weight was inversely proportional to the reservoir depletion, and it was evaluated to be at an average degree of 0.03%.
- It was observed that reservoir depletion commenced when drilling was at the pay zone. At this point, high pressure was experienced in the open hole due to pressure drawdown associated with the ex-solution of dissolved gas in the hydrocarbon oil. It was evidenced that there exists a direct proportional relationship between equivalent mud weight and pore pressure, while the reservoir depletion is inversely proportional to the wellbore pore pressure.
- The average reservoir depletion degree from the oil production performance data was estimated to be 0.81% with an average pressure drawdown of 156 psi, and the solution gas drive was only effective between the duration of 0 to 3 years.
- The average evaluated reservoir depletion degree was 0.03% with an average pressure drawdown of 147 psi at the drilling stage, while at the producing stage it was 0.81% with an average pressure drawdown of 156 psi. The observed proportional relationship between the evaluated degrees of reservoir depletion in terms of ratio was 0.03:0.81.
- The model’s oil recovery factor for the solution gas drive mechanism was estimated to be 27%. The estimated 27% ultimate oil recovery of the solution gas drive mechanism was between the standard limit of less than 5% to about 30%.

Nomenclature

Bp = bubble point pressure, psi
Db = first depletion, psi
De = last depletion, psi
EMW = equivalent mud weight, ppg
EMWc = rate of change of equivalent mud window, %
EMWr = rate of equivalent mud window, %
GOR = gas-to-oil ratio, scf/STB
IBM SPSS = international business machines statistical package for the social sciences
LWD = logging while drilling
MD = measuring depth, ft.
MW = Mud weight, ppg
n = number of iteration
OOIP = original oil in place, mmbbl
Pr = monthly oil rate production, bbl/month
PR = pore pressure, psi
PWF = flowing bottom-hole well pressure, psi
Rr = rate of reservoir depletion during production, %
RW = reservoir depletion experienced at wellbore while drilling, %
SDW = safe drilling window
SFG = Shear-Failure-Gradient, psi/ft.
SST = *anonymous*
TVD = total vertical depth, ft.

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APPENDIXES

APPENDIX 1: REGRESSION OUTPUT FOR THE RELATIONSHIP BETWEEN EQUIVALENT MUD WEIGHT AND PORE PRESSURE

Table A1.1: Regression analysis for the relationship between equivalent mud weight and pore pressure

Model Description

Model Name		MOD_4
Dependent Variable	1	emw
Equation	1	Power[a]
Independent Variable		pr
Constant		Included
Variable Whose Values Label Observations in Plots		Unspecified

a. The model requires all non-missing values to be positive.

Case Processing Summary

	N
Total Cases	48
Excluded Cases[a]	43
Forecasted Cases	0
Newly Created Cases	0

a. Cases with a missing value in any variable are excluded from the analysis.

Variable Processing Summary

		Variables	
		Dependent	Independent
		emw	pr
Number of Positive Values		5	5
Number of Zeros		0	0
Number of Negative Values		0	0
Number of Missing Values	User-Missing	0	0
	System-Missing	43	43

Model Summary and Parameter Estimates

Dependent Variable: emw

Equation	Model Summary					Parameter Estimates	
	R Square	F	df1	df2	Sig.	Constant	b1
Power	.910	30.282	1	3	.012	1.516	.240

The independent variable is pr.

APPENDIX 2: FREQUENCY CURVE ANALYSIS OUTPUT FOR THE APPLICATION OF EQUIVALENT MUD WEIGHT AND WELLBORE PORE PRESSURE (RATE AND RATE OF CHANGE OF EQUIVALENT MUD WEIGHT)

Table A2.1: Frequency curve analysis for the rate of EMW (EMW_r) application on pore pressure (P_R)

Descriptive Statistics

	N	Range	Minimum	Maximum	Sum	Mean		Std. Deviation	Variance	Kurtosis	
	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic	Statistic	Statistic	Std. Error
RateofEMW	5	123	0	123	446	89.20	22.500	50.311	2531.200	4.675	2.000
Valid N (listwise)	5										

Table A2.2: Frequency curve analysis for rate of change of EMW (EMW_c) application on P_R

Descriptive Statistics

	N	Range	Minimum	Maximum	Sum	Mean	Std. Deviation	Variance
ROCEMW	5	23	0	23	46	9.20	8.438	71.200
Valid N (listwise)	5							

APPENDIX 3: REGRESSION OUTPUT FOR THE RELATIONSHIP BETWEEN WELLBORE PORE PRESSURE AND RESERVOIR DEPLETION

Table A2.1: The relationship between wellbore pore pressure and reservoir depletion curve fitting and frequency analysis.

Model Description

Model Name		MOD_4
Dependent Variable	1	PR
Equation	1	Power[a]
Independent Variable		Rw
Constant		Included
Variable Whose Values Label Observations in Plots		Unspecified

a. The model requires all non-missing values to be positive.

Case Processing Summary

	N
Total Cases	5
Excluded Cases[a]	0
Forecasted Cases	0
Newly Created Cases	0

a. Cases with a missing value in any variable are excluded from the analysis.

Variable Processing Summary

		Variables	
		Dependent	Independent
		PR	Rw
Number of Positive Values		5	5
Number of Zeros		0	0
Number of Negative Values		0	0
Number of Missing Values	User-Missing	0	0
	System-Missing	0	0

Model Summary and Parameter Estimates

Dependent Variable: PR

Equation	Model Summary					Parameter Estimates	
	R Square	F	df1	df2	Sig.	Constant	b1
Power	.965	83.337	1	3	.003	146.592	-.875

The independent variable is Rw.

APPENDIX 4: FREQUENCY CURVE ANALYSIS OUTPUT OF THE ESTIMATED RESERVOIR DEPLETION DEGREE FROM THE OIL PRODUCTION LOG

Table A4.1: Frequency curve analysis for rate of reservoir depletion degree from the oil production performance log.

Statistics

Rw

N	Valid	5
	Missing	0
Mean		.0280
Std. Error of Mean		.01114
Std. Deviation		.02490
Minimum		.01
Maximum		.07

Rw

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	.01	2	40.0	40.0	40.0
	.02	1	20.0	20.0	60.0
	.03	1	20.0	20.0	80.0
	.07	1	20.0	20.0	100.0
	Total	5	100.0	100.0	

Statistics

Rdp

N	Valid	45
	Missing	0
Mean		.8143
Std. Error of Mean		.03715
Std. Deviation		.24924
Variance		.062
Range		1.13
Minimum		.00
Maximum		1.13