Estimation of Permeability from Laser Particle Size Analysis: A Case Study of Selected Wells Offshore Niger Delta

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***Abstract*— Within the first few years of production, most producing companies experience poor reservoir performance largely because of inadequate reservoir properties description and one of these misrepresented properties is Permeability. The Permeability of the Deep offshore Niger Delta was estimated by analyzing thirty-five (35) samples from four wells; Well A, Well B, Well C and Well D. The samples were put in a Microtrac S3000 Laser Particle Size Analysis (LPSA) machine and core plugs were put in the Permeameter for Permeability estimation. The analyzed sample results were compared with the existing permeability models of the area. The wells were observed to have very good permeability ranging from 700mD to 5500mD. Comparing the results from the different methods of Permeability estimation, the Laser Particle Size Analysis machine was found to be the most precise given its inherent unbiased algorithms which neutralize any form of regional heterogeneity. Krumbein and Monk's, and Van Baaren's models correlates closely with measured permeability while Berg's proved inaccurate for prediction of permeability in this region. Reservoir Engineers and Petrophysicists interested in Offshore Niger Delta would find this work effective for more accurate permeability estimation.**

***Key words*— Permeability, Grain size, Niger Delta, Model, LPSA**.

I. INTRODUCTION

Permeability governs the ease with which fluids move through hydrocarbon reservoirs, aquifers and other materials. In hydrocarbon recovery, permeability is one of the petrophysical properties which must be ascertained in order to obtain the production capacity of the reservoir and to determine the economics of production. There are different types of permeability which are differentiated based on presence or absence of other fluids (fluid flow). They are; relative, effective and absolute permeability. In hydrocarbon production, the most important type of permeability is the relative permeability which addresses the flow of multiple fluids occupying the same void in the reservoir. Reservoirs contain gas, oil or water in varying quantities interfering with each other and this interference depends on the number, geometry and interconnectivity of pores.

Darcy's law which explains the steady state flow of fluid through a porous media is used to determine Permeability. More conveniently empirical models are used in estimation of permeability remotely, especially using information from logs. But this method has proved not to be very reliable. A more precise way of measuring Permeability involves the laboratory measurement of the flow of fluid passing through standardized conditions with the use of permeameter which was employed in this work. But this method is expensive and demanding.

The factors that influence Permeability include but are not limited to grain behavior such as size, roundness, sphericity, roughness and packing as well as sorting and other rock altering processes like fracturing, dolomitization, dissolution which create additional porosity.

According to [1], the Southeastern offshore Niger Delta alone covers some six thousand (6000) square miles which is roughly one-tenth of the entire basin. Yet it is known to deliver 550,000 b/d oil which is more than one quarter of Nigeria's 1.85 million b/d oil OPEC quota, as well as 110,000 b/d condensate. It is in this manner completely important to give a point by point investigation of one of the main considerations that influence producibility of rocks. Given the predominantly fine grain sizes in the Offshore Niger Delta, there is a high tendency for a reduction in the Hydrocarbon pathways and flow obstruction, hence decreased permeability.

Reference [2], [3], [4], [5] and other researchers have all worked on the estimation of Permeability based on grain size, porosity, sorting, packing and grain shapes. And hence, developed empirical equations and models. But the reliability of this models varies form locality to locality, as these models have been seen to not to yield accurate results in different regions. This is majorly due to the physical and chemical heterogeneity of the different regions. Consequently, it is important to ascertain the best fit model for the estimation of permeability in the Niger Delta by comparison to the LPSA machine (Microtrac S3000) predicted values.

II BRIEF THEORY

Permeability deals with the capacity of the reservoir-rock to conduct and transmit fluid. It is a key parameter in all reservoir analysis and examinations. The rock permeability frequently indicated by k, is an essential formation property since it controls the directional development and the stream rate of the reservoir-fluids in the formation. Darcy's law is the fundamental equation defining permeability.

$$v = \frac{k}{\mu}\frac{dp}{dL} \quad (1)$$

$$Q = -KA\frac{dp}{dL} \quad (2)$$

Where v = apparent fluid flowing velocity, cm/sec

k = proportionality constant, or permeability, Darcy's

μ = viscosity of the flowing fluid, cp

dp/dL = pressure drop per unit length, atm/cm

Q is the flow rate or the total discharge per unit time in cm^3/s

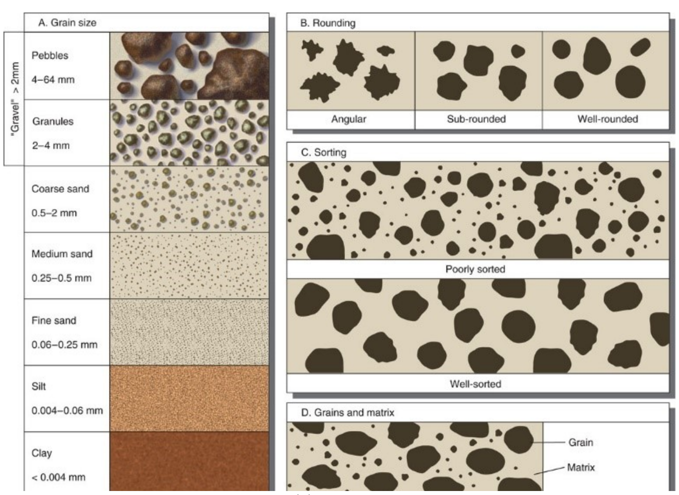
K is Permeability in Darcy

A is Cross sectional Area of the flow path in cm^2

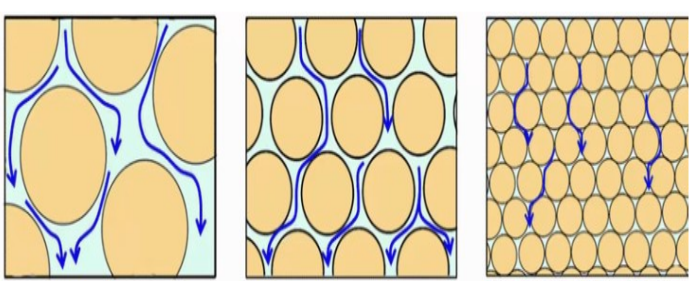
L is the length of the flow path in cm

Permeability is a function of pressure. Often, the pressure dependence is ignored in reservoir calculations, but the disparity with position can be pronounced. In general, the permeability varies by several magnitudes, and such variation will in the process influence any oil recovery.

Darcy set up that the Permeability which will allow stream of one centipoise liquid to stream at direct speed of one cm for each second under a pressure of one centimeter for every centimeter and beneath.



(a)



(b)

Fig.1: Grain property (a) and Pores connectivity (b) [6][7].

Fig.1 shows grain properties (size, shape and sorting). The blue arrows represent the flow path, it could be seen that the ease of flow (permeability) decreases from left to right owing to the reduction in grain size.

A. Grain size determination

In the characterization of Sedimentary rocks under surfaces, five noteworthy properties are considered. They are as per the following; size of the particles, shape or sphericity of the grains, roundness of the particles, mineralogical organization and grain sorting. Be that as it may, the grain size is the most essential textural highlight of particles. This is on the grounds that it decides the order of particles and in this way the kind of rock and consequently generally influences porosity and permeability of the subsequent rocks and their capacity to have hydrocarbon or something else. Grain Size is likewise integral asset in silt geochemistry as certain cations would just be specially adsorbed by grains of a specific size. Grain Size which is likewise molecule size can be alluded to as the distance across of individual grains of residue, or lithified particles in clastic rocks. There are diverse procedures for the assurance of grain sizes however the most well-known ones are mechanical sieving for coarse materials and the pipette technique utilizing Stoke's Law of settling speeds for the fine-grained particles.

Grain size distribution investigation can likewise be performed for the accompanying reasons:

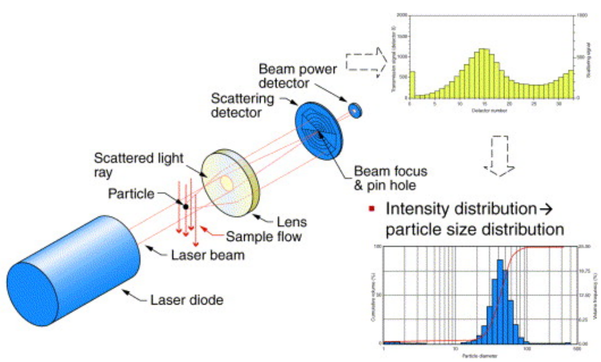
1. Grain size investigation is a powerful apparatus for deciding penetrability, condition of statement, textural properties, residue transport systems and the quality of the depositional medium.
2. Grain analysis helps in the assurance of the skyline to set the well to begin production
3. It aids in the operation of gravel packing pressing by giving the applicable data on grain pressing and grain measure.

B. Laser Particle Size Analyzer

Microtrac S3000 is an automatic machine with a magnetic stirrer which mixes the sample together and sends it into the laser beam for measurement to take place. This instrument is a digital imaging device, that measures the angle of light scattered by the particles as they pass through a beam of light. This machine operates on Francoeur's diffraction theory that states that the intensity of light scattered by a particle is proportional to the particle size [8]. But the angle of the laser beam is inversely proportional to the particle size [9]. Hence by just measuring the intensity of scattered light, the particle size can be determined. The LPSA therefore does two important things:

1. Measures scattered light angle intensity
2. Transform that scattering data into particle size distribution (seeFig.2b)

(a)



(b)

Fig.2: A Microtrac S3000 LPSA (a) and Microtrac S3000 LPSA operating principle procedure [10].

III. METHODOLOGY

The samples were collected from Deep Offshore Niger Delta from four different wells (Well A-D) that are located an average of seven hundred (700) miles apart in this Field. A total of thirty-five (35) samples were collected per well. These samples were then analyzed in the laboratory after which the Microtrac S3000 was used to estimate the Mean, Standard Deviations and the permeability.

Microtrac S3000 is an automatic machine with a magnetic stirrer which mixes the sample together and sends it into the laser beam for measurement to take place. The results are displayed and automatically plotted. Permeability was then estimated based on the auto generated grain parameters. The Ultra Perm 500 Permeameter was used to calculate Permeability.

This technology is associated with improved accuracy and consistency. Even in the submicron range, measurements are made without the sample-to-sample variation evident in many other systems. By increasing the number of laser sources, Microtrac Inc.'s Tri-Laser technology makes a more effective use of photo-detection devices, part of the critical and sensitive components of the measurement system. The Microtrac S-3000 offers these important benefits:

1. Accuracy – A unique Tri-laser and multi detector optical system greatly improves resolution through the entire range of the S-3000 and enhances the submicron range.
2. Consistency – The S-3000 series delivers repeatability and linearity, time after time.
3. Range – Measurement accuracy from 0.024 to 2800 microns makes the S-3000 ideal for a wide range of applications.
4. Dry and Wet options – A variety of wet and dry sample delivery systems are available to interface to the S-3000 optical system. Thishigh flexibility allows for easy switch zone from wet to dry for any measurement.

A. Permeability Estimation

The LPSA estimated permeability was compared with permeability derived from using [2], [3], and [4]. For the models that incorporate porosity, a thirty percent (30%) porosity was applied. This is the average porosity derived from the core plugs from which the analyzed sample was gotten. The models are shown below:

The Permeability for the data gathered from the wells was calculated using three (3) established models:

I. The Krumbein and Monk Model:

$$K\ (m^2) = (7.5 \text{ x } 10^{-10})\ G^2\ e^{-1.31\sigma} \qquad (7)$$

$$K = 760 d_g^2 \exp(-1.31\ \sigma_D) \qquad (8)$$

II. The Berg's Equation:

$$K = 5.1 \text{ X } 10^{-6}\ \Phi^{5.1} d^2 e^{-1.385p} \qquad (9)$$

$$K = 80.8 \Phi^{5.1} d^2 e^{-1.385p} \qquad (10)$$

III. The Van Baaren's model:

$$K = 10 d_d^2\ \Phi^{3.64 + m}\ C^{-3.64} \qquad (11)$$

$$K_{ps} = 18.8 d_d^2 \Phi^{3.64 + m} \qquad (12)$$

Where:

G is the geometric mean particle size (in mms)

K is given in Darcies/ millidarcies

d_g is the geometric mean grain diameter (in mm)

σ_D is the standard deviation of grain diameter in phi units, where phi=$-\log_2(d)$ and d is expressed in millimeters

d is the median grain diameter (in mm)

Φ is porosity in percent/fraction

p is a sorting term

d is median grain diameter (in mm)

Φ is fractional porosity

m is Archie cementation exponent

C is a sorting index that ranges from 0.7 for very well sorted to 1.0

K_{ps} is permeability for poorly sorted sandstone in millidarcy

To account for a range of grain sizes, Berg considered two mixtures of spheres and assumed that K will be controlled primarily by the smaller grains. This introduces a sorting term $p=P_{90}-P_{10}$, called the percentile deviation, to account for the spread in grain size. The p term is expressed in phi units, where $phi=-\log_2 d$ (in mm). The model links petrological parameters such as grain shape, sorting and grain size to permeability which is very remarkable.

Studies have shown that m is a function of compaction due to overburden pressure, depth of burial, shape and distribution of pore geometry particularly in vuggy and fractured formations[11]. For poorly cemented sandstone sediments, m is usually taken to be less than 2, and more than 2 when grains are well cemented. Therefore, for the offshore Niger Delta, the Archie's cementation exponent m has been taken to be 2. From the grains size parameters obtained from the laboratory analysis with the use of Microtrac S3000, the permeability is calculated for the different wells.

The sorting parameters relevant for the calculationwere then compiled (see Table1) and converted to their required standard units,and the above models were then used to estimate the permeabilities.

IV. RESULTS AND DISCUSSION

The results of the grain size distribution and sorting parameters are given in fig.3 and table1respectively. A comparative permeability estimated using three (3) established models, LPSA and Permeameteris showed in table 2 below.

From the results, the Permeability of the Offshore Niger Delta ranges from 750 mD to 5500mD which is a rather wide estimate. This wide estimate is due to the variety of methods used in the determination of permeability. However, looking at LPSA machine estimates the permeability of the Offshore Niger Delta ranges from about 1500mD to 4500mD. Also considering the permeabilities as measured by the Permeameter, 1542mD to 4116mD was observed. In the Niger Delta, there have been predictions of permeability ranging from 2200mD to 5789mD for areas with excellent permeabilities. However, rocks with smaller grain sizes relatively have smaller permeabilities than their larger grain counterparts. The reason is this, smaller grain sizes produce smaller pores, and more importantly, smaller pore throats, which restrict the fluid flow more than larger grains which produce larger pore throats. The Deep offshore Niger Delta is predominantly made of fine-grained materials which would naturally block pore throats and hence reduce permeability considerably. Therefore, it is no surprise that some of the calculations yielded lower permeabilities than others.

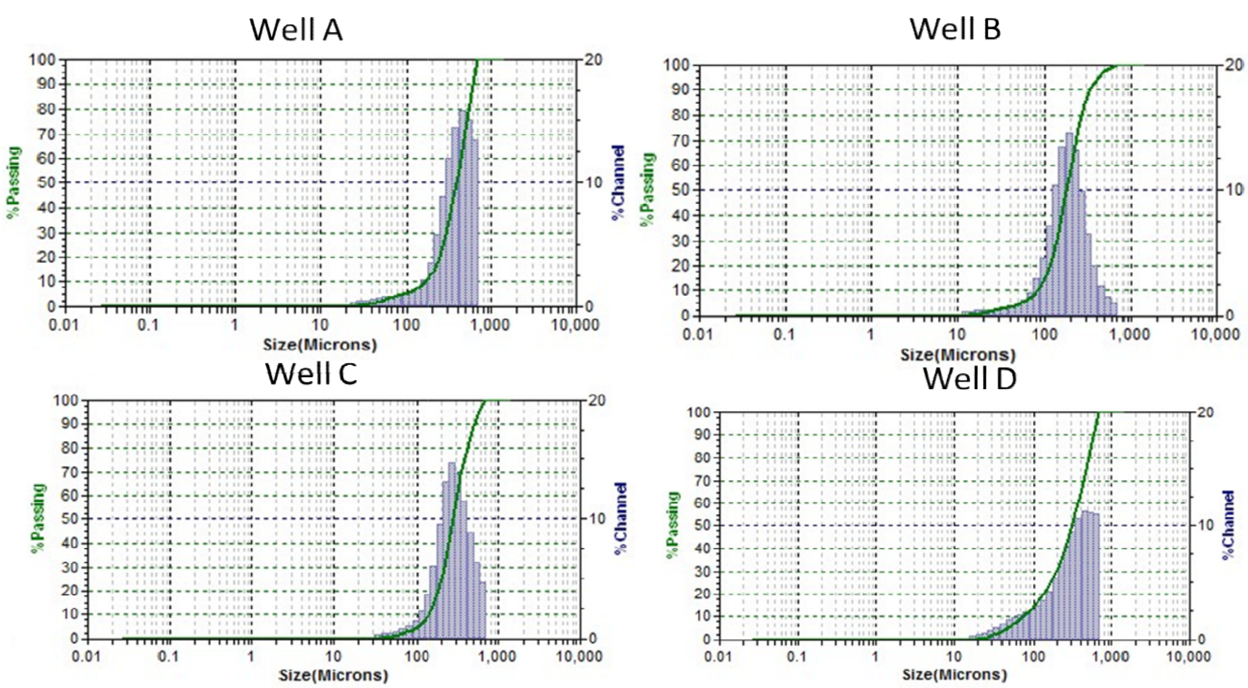


Fig.3: Statistical dispersion of Well the wells

Table 1: Sorting Parameters

Parameters	Well A	Well B	Well C	Well D
Standard deviation (phi)	2.5060	3.416	2.8470	2.1851
Mean grain diameter (mm)	0.0450	0.0235	0.0812	0.0333
Modal grain diameter (μm)	393.4	183.0	280.7	317.8
Median grain diameter (mm)	0.3934	0.1830	0.2807	0.3178
Percentile P ($P_{90} - P_{10}$) (phi)	1.1629	1.9569	1.438	0.9214

The permeability of Well 'A' as calculated from Van Baaren, and Krumbein and Monk's model is in close range with the LPSA machine's estimate. Though the Krumbein and Monk model gave the closest estimate when compared with the LPSA and Permeameter values. The Berg model for well A were impractical as they were observed to underestimate (Berg I) and overestimate (Berg II) the permeability. The average permeability of Well A is 1677mD and was calculated by taking an average of the permeability of all the methods used.

For Well 'B', Krumbein and Monk's model yielded permeability that is closer to the Microtrac S3000 estimated permeability. The Van Baaren's model under predicted the permeability while the Berg model predicted even far worst values. It is important to note that both models have the porosity component, and this could be attributed to the constant porosity incorporated into the model, since an average porosity value of 30% was used. The average permeability from the methods used is 2979 mD.

The Permeability of Well 'C' has all the methods agreeing and this could mean that Well C permeability is the most accurate of all. However, the most accurate permeability value which incorporates regional heterogeneityinto its results is the Microtrac S3000 estimate. The average permeability of Well C is 1795 mD.

The Permeability of Well 'D' follows Well B trend, in the sense that the value of Krumbein and Monk's model is much closer to the Microtrac S3000 estimated and permeameter values than that of Van Baaren. While the values for Berg's model shows high disparity. The average permeability of Well D is 3,727 mD.

Table 2: Compilation of Results

MODELS	WELL A	WELL B	WELL C	Well D
Krumbein and Monk	1,370	5,105	1,267	5,322
Berg I	8.5×10^{-9}	5.5×10^{-9}	6.3×10^{-9}	3.9757×10^{-9}
Berg II	134,859	0.0876	100,500	0.06299
Van Baaren I	772	848	1,996	2,559
Van Baaren II	3,271	708	1,666	2,135
Microtrac S3000 (LPSA)	1,429	4,300	1,935	4,503
Permeameter	1,542	3,936	2,110	4,116

Well D is the most permeable well while the least permeable well in this Field is Well A. From the average values, permeability in this Field ranges from 1650 mD to 3750 mD. Considering this value, the Offshore Niger Delta has a very good permeability and if all other petrophysical properties are properly estimated, the reservoir is likely to produce for a long time without any significant problem. The rock's permeability is one of the most important parameters necessary for effective reservoir characterization and management [12]. Therefore, it must be noted that for the Offshore Niger Delta, the permeabilities are within these ranges as given by the Models and Microtrac S3000.

The Berg's model did not work for any of the wells and the model has been known not to be applicable with porosity values that are less than thirty percent (30%) and this is the average porosity of the collected Offshore Niger Delta samples measured from the cores. This porosity value and percentile differences incorporated into the model could be the reason the model yielded the suppose permeability.

V. CONCLUSION

The established permeability for the offshore Niger Delta ranges from 700mD to 5500mD covering the values from Krumbein and Monk, and Van Baaren's models as well as the Microtrac S3000 and Ultra Perm 500 Permeameter values.The results from comparing these three sets of permeabilities proves the assertion that regional heterogeneity and a bulk of other factors that affect permeability should make the empirical grain-based permeability models a last resort.Caution should be applied while using empirical based models for permeability estimation particularly models that incorporate other parameters such as porosity, cementation factor and percentile distribution. For estimation of permeability in the Niger Delta, it is important to note that Microtract S3000 is best for estimating permeability, since it estimate correlated best with the Permeameter's permeability but in it absence, Krumbein and Monk, and Van Baaren model could be used for prediction of permeability within this region but priority should be given to Krumbein and Monk since it estimated values correlates better. while Bergs model should be avoided since it showed a great disparity with the measured permeability.

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