PETROPHYSICAL ATTRIBUTES AND RESERVOIR PRODUCTIVITY INDEX OF ETA-1 WELL, X-FIELD, NIGER DELTA. NIGERIA

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INTRODUCTION

Reserve estimation therefore, is based on the field wide distribution of these reservoir properties. Due to the intense petroleum exploration and exploitation activities in the Niger Delta region during the last two decades, vast amount of data have been accumulated from which it had been possible to establish the historical reconstruction and evolution of the Niger Delta basin .

This research work is on the application of wireline logs to identify and quantify hydrocarbon reserves and evaluate rock properties in part of the offshore Niger Delta. The petrophysical analyses of the wireline logs provide reservoir characteristics (porosity, permeability and fluids saturation). Quantitative determination of fluid transmissivity (layer thickness times permeability) will be an added advantage to further characterize reservoir rocks. Integrating these two parameters would guide and provide a good knowledge of the potential of porous media and enhance exploration and development of the reservoir rocks.

LOCATION OF STUDY

The field under study is pseudo-named “X’’ field in accordance with the Shell (SPDC) confidentiality agreement. The field is located in the offshore Niger Delta but the co-ordinates of the location of this field were concealed due to proprietary reasons.

SOURCE ROCKS OF THE NIGER DELTA

Source rocks are rocks containing organic matter that is converted to petroleum by burial and other post depositional changes. The Agbada Formation has intervals that contain organic -carbon contents sufficient to be considered good source rock. The intervals, however, rarely reach thickness sufficient to produce world class oil province and are immature in various parts of the delta .

The Akata Shale is present in large volumes beneath the Agbada Formation and is at least volumetrically sufficient to generate enough oil for a world class province such as the Niger Delta. Ejedawe et al., (1984) used maturation models to conclude that in the central part of the delta, the Agbada shale sources the oil while the Akata shale sources the gas. In other parts of the delta, they believed that both shales source the oil.

MIGRATION OF PETROLEUM IN THE NIGER DELTA

Migration is principally movement along permeability paths and fluids potential gradients; it may be over short distances like from source rock to reservoir rock over long distance like within the reservoir rock . Growth faults act as migratory paths enabling the hydrocarbons to be generated in the Akata shale thus enabling the hydrocarbons to migrate and accumulate in the Agbada reservoir sands .

Sands juxtaposed across a fault are often connected. Hunt (1990) related episodic expulsion of petroleum from abnormally pressured, matured source rocks to fracturing/ resealing of the over pressured interval.

METHODOLOGY

DATA SOURCE

The wireline geophysical well logs used in the research work were provided by Shell Development Company of Nigeria Limited, Port Harcourt.

CALCULATION OF POROSITY (∅)

Reservoir A
USING FORMULA:

$$\phi_{Den} = \left(\frac{p_{ma-}p_{blog}}{p_{ma-}p_{f}}\right) - V_{sh} \times \left(\frac{p_{ma} - p_{sh}}{p_{ma-}p_{f}}\right)$$

Where ϕ_{Den} = porosity derived from density log

ρ_{ma} = Density of matrix = 2.65g/cm^3

ρ_{blog} = Bulk density value on density log =2.11g/cm^3

ρ_f = 1.0g/cm^3

V_{sn} = volume of shale = 0.20

ρ_{sn} = 2.30g/cm^3

By Substitution,

$$\phi = \left(\frac{2.65 - 2.11}{2.65 - 1.0}\right) - 0.20 \times \left(\frac{2.65 - 2.30}{2.65 - 1.0}\right)$$

$$\phi = \left(\frac{0.54}{1.65}\right) - 0.20 \times \left(\frac{0.35}{1.65}\right)$$

ϕ = 0.33 – 0.20 x 0.212

ϕ = 0.33 – 0.042

ϕ = 0.29 or 29%

Reservoir B

$$\phi_{Den} = \left(\frac{p_{ma-}p_{blog}}{p_{ma-}p_{f}}\right) - V_{sh} \times \left(\frac{p_{ma} - p_{sh}}{p_{ma-}p_{f}}\right)$$

ϕ_{Den} = porosity derived from density log

ρ_{ma} = Density of matrix = 2.65g/cm^3

ρ_{blog} = Bulk density value on density log =2.26g/cm^3

ρ_f = 1.0g/cm^3

V_{sn} = volume of shale = 0.25

ρ_{sn} = density of shale = 2.32g/cm^3

By Substitution,

$$\phi = \left(\frac{2.65-2.26}{2.65-1}\right) - 0.25 \times \left(\frac{2.65-2.32}{2.65-1}\right)$$

$$\phi = \left(\frac{0.39}{1.65}\right) - 0.25 \times \left(\frac{0.33}{1.65}\right)$$

ϕ = 0.236 – 0.25 x 0.2

ϕ = 0.236 – 0.05

ϕ = 0.19 or 19%

CALCULATION OF IRREDUCIBLE WATER SATURATION (Swirr)

Reservoir A

Swirr = $\left[\frac{F}{2000}\right]^{1/2}$

Where F = 0.00044

By substitution,

Swirr = $\left(\frac{0.00044}{2000}\right)^{1/2}$

Swirr = $(0.00000022)^{1/2}$

Swirr = 0.00045

Reservoir B

Swirr = $\left[\frac{F}{2000}\right]^{1/2}$

Where F = 0.0011

By substitution,

Swirr = $\left(\frac{0.0011}{2000}\right)^{1/2}$

$= (0.00000055)^{1/2}$

Swirr = 0.00074

Therefore, Swirr at reservoir A = 0.00045 and Swirr at reservoir B = 0.00074

CALCULATION OF PERMEABILITY (K)

K = $\frac{0.136 \times \phi^{4.4}}{(Swirr)^2}$

Reservoir A

Where ϕ = 0.29 and Swirr = 0.00045

K = $\frac{0.136 \times 0.29^{4.4}}{(0.00045)^2}$

K = $\frac{0.136 \times 0.00431}{2.025 \times 10^{-7}}$

K = $\frac{0.000586}{2.025 \times 10^{-7}} = 2895md$

Reservoir B

K = $\frac{0.136 \times \phi^{4.4}}{(Swirr)^2}$

Where ϕ = 0.19 and Swirr = 0.00074

K = $\frac{0.136 \times 0.19^{4.4}}{(0.00074)^2}$

K = $\frac{0.136 \times 0.000671}{5.48 \times 10^{-7}}$

K = $\frac{0.0000913}{5.48 \times 10^{-7}} = 166.5md$

CALCULATION OF TRANSMISSIVITY

Transmissivity (T) = Permeability x Reservoir's thickness

Reservoir A

Where permeability = 2895md and reservoirs' thickness = 129 feet

Transmissivity (T) = 2895 x 129 = 373 455md ft

Reservoir B

Transmissivity (T) = permeability (K) x reservoir thickness

Where Permeability = 166.5md reservoirs thickness = 90ft

Transmissivity = 166.5 x 90 = 14985mdft

CALCULATION OF WATER SATURATION (S_w)

Water saturation (S_w) = $\left(\frac{Ro}{Rt}\right)^{1/2}$

Where Ro = Resistivity of water bearing rock

Rt = True resistivity of the rock.

Reservoir A

Where Ro =3.241ohm-metres and Rt=599.438 ohm-metres

$S_w = \left(\frac{3.241}{99.438}\right)^{1/2} = (0.0326)^{1/2} = 0.18$

Reservoir B

Where Ro = 2.268 ohm-metres and Rt = 2.4.428 ohm-metres

$S_w = \left(\frac{2.268}{24.428}\right)^{1/2} = (0.0928)^{1/2} = 0.30$

CALCULATION OF HYDROCARBON SATURATION (S_H)

$S_H + S_w = 1$

$S_H = 1 - S_w$

Reservoir A

Where $S_w = 0.18$

$S_H = 1 - 0.18$

$S_H = 0.82$

Reservoir B

Where $S_w = 0.30$

$S_H = 1- 0.30$

$S_H = 0.70$

CALCULATION OF BULK VOLUME OF WATER (BVW)

Bulk volume water (BVW) = Porosity (Ø) x saturation water (S_w)

Reservoir A

Where $\phi = 0.29$ and $S_w = 0.18$

Bulk volume water (BVW) = 0.29 x 0.18 = 0.052

Reservoir B

Where $\phi = 0.19$ and $S_w = 0.30$

Bulk volume water (BVW) = 0.19 x 0.30 = 0.057

Table 1: PETROPHYSICAL QUANTITATIVE ANALYSIS ETA-1 WELL

Reservoirs	Gross Thickness of Sands(ft)	Net Thickness of Sands(ft)	N/G Ratio	ϕ (%)	Swirr	SW (%)	SH (%)	BVW	K (MD)	T(mdft)
A	129	103.5	0.802	29	0.00045	18	82	0.052	2895	373,455
B	90	80	0.889	19	0.00074	30	70	0.057	166.5	14,985

PETROPHYSICAL RESULTS AND INTERPRETATION

Total of two hydrocarbon reservoirs were identified and evaluated. The following petrophysical parameters were quantitatively analyzed for the reservoirs: Volume of Shale (V_{sh}), Porosity (ø), formation factor (F), Irreducible water saturation (S_{wirr}), permeability (K), water saturation (S_w), Hydrocarbon saturation (S_h) and Bulk volume water (BVW). The results are summarized in Table 1 and 2.

The reservoir B is found at the interval of 7673 – 7761ft (2339-2366m) and has a gross (G) and net (N) thickness of sand, 88ft (26.8m) and 70.5ft (21.5m) respectively, with N/G ratio of 0.80; water saturation (S_w) of 14% and hydrocarbon saturation (S_h) of 86%, porosity (ø) and permeability (K) of 25% and 997.8md respectively. Its transmissivity is 87806mdft. (Table 1).Therefore, reservoir B has very good porosity and very good permeability.

The formation bulk volume water values calculated are nearly constant (Table 1) and this shows that the reservoir is homogeneous and is at irreducible water saturation (S_{wirr}) and therefore can produce water – free hydrocarbon. The transmissivity in reservoir A is higher than of B. This means that lateral migration of hydrocarbon from reservoir to a well bore will be easier in A than B.

CHARACTERISTICS OF RESERVIORS OF ETA-1WELL

There are two hydrocarbon reservoirs found in the wel. These are reservoirs A and B.

Reservoir A occurs at the interval of 5693 – 5822ft (1735-1775m) and has a gross (G) and net (N) thickness of sand, 129ft (39.3m) and 103.5ft (31.5m) respectively with N/G ratio of 0.8; water saturation (S_w) of 18% and hydrocarbon saturation (S_h) of 82%; porosity (ø) and permeability (K) of 29% and 2895md respectively while its transmissivity is 373455mdft . Therefore, the reservoir has very good porosity and excellent permeability.

Reservoir B occurs at the interval of 7672 – 7762ft (2338-2366m) and has a gross (G) and net (N) thickness of sand, 90ft (27.4m) and 80ft (24.4m) respectively, with N/G ratio of 0.9; water saturation (S_w) of 30% and hydrocarbon saturation (S_h) 70%, porosity (ø) and permeability (K) of 19% and 166.5md respectively. Its transmissivity is 14985mdft. Therefore, the reservoir has both good porosity and permeability.

The formation bulk volume water values calculated are nearly constant and this shows that the reservoir is homogeneous and is at irreducible water saturation (S_{wirr}) and therefore, can produce water – free hydrocarbon. The transmissivity in reservoir A is far much greater than the reservoir B, this means that the hydrocarbon in reservoir A will flow easier to the well bore than B.

GENERATING EMPIRICAL RELATIONSHIP BETWEEN DEPTH, POROSITY AND PERMEABILITY

From the petrophysical values, both the porosity and permeability decreases down the depth (Table 1). Therefore, empirical formulas can be generated to show the relationship between (1) depth and porosity, (2) depth and permeability. These formulae can be derived from below:

Since the porosity varies inversely with depth (D) the relationship between porosity (∅) and depth can be written as

$$D \propto \frac{1}{\phi} \quad \text{-------------------------(1)}$$

Let m represents the constant between depth and porosity.

$$\text{Then, } D = \frac{m}{\phi} \quad \text{--(2)}$$

From the graph below, variables of depth (D) and porosity were taken and empirical formula between depth and porosity can be derived in below:

TABLE 2: RESERVOIR SAND/SHALE PERCENTAGE CALCULATIONS FOR SIX WELLS.

WELL BONN 013		
RESERVOIRS	**% SAND**	**% SHALE**
A	80	20
B	75	25

$D_2 - 1$ **Fig. 22c: Graph of reservoir sand / shale percentage for well Bonn 013.**

$\psi_2 - \psi_1$ ---(3)

Where:
D_2 = 8432ft
D_1 = 5800ft
$\emptyset_1$ = 17% or 0.17
$\emptyset_2$= 28% or 0.28

By substitution,

$$8432 - 5800 = \frac{m}{0.28 - 0.17}$$

$$2632 = \frac{m}{0.11}$$

m = (2632ft) x (0.11) -- (4)

The empirical formula between depth (d) and porosity can be written as:

$D = 289.52\emptyset^{-1}$ ---(5)

Therefore, $\emptyset = 289.52\ D^{-1}$ ---(6)

Where:
D= depth (feet)
$\emptyset$ = porosity.

Depth is in feet can be converted into metres as follow:

2632 x 0.3048 = 802.2 metres (1 foot = 0.3048m) ----------------(7)

From the above eq

Fig. 22d: Graph of reservoir sand / shale percentage for well Bonn 015.

m = 802.2 x0.11
m = 88.25

The empirical formula between depth and porosity can be written as:

$D = 88.25\emptyset^{-1}$ --(8)

Therefore, $\emptyset = 88.25\ D^{-1}$--(9)

Where:
D = depth (metres).
$\emptyset$ = porosity

Similarly, the empirical formulas between depth (ft) and permeability (k) can be derived in below:
Permeability (k) decreases as the depth increases.

$$D \propto \frac{1}{K}$$

GRAPHICAL DETERMINATION OF IRREDUCIBLE WATER SATURATION CONSTANT (SWIRR) LEADING TO EMPIRICAL FORMULA BETWEEN POROSITY AND PERMEABILITY

From the Dresser Atlas equation of Permeability,

$$K = \frac{0.136 \times \phi^{4.4}}{(swirr)^2}$$

$$(swirr)^2 = \frac{0.36 \times \phi^{4.4}}{k} \qquad \text{……………………………(10)}$$

$$swirr = \sqrt{\frac{0.36 \times \phi^{4.4}}{K}} \qquad \text{……………………………(11)}$$

Let B = 0.36 x $\phi^{4.4}$

Equation becomes

$$swirr = \sqrt{\frac{B}{K}} \qquad \text{…………………………………..(12)}$$

$$(swirr)^2 = \frac{B}{K} \qquad \text{……………………………………(13)}$$

Table 7 showing variation of porosity and permeability which was used to plot the graph of B against K inorder to determine the irreducible water saturation constant.

Slope of the graph (Fig. 25) can be derived as

$$S = \frac{B_2 - B_1}{K_2 - K_1} \qquad \text{…………………………………(14)}$$

Where:

$B_2 = 58.6 \text{ x}10^{-5}$

$= 0.000586$

$B_1 = 17.4 \text{ x}10^{-5}$

$= 0.000174$

$K_2 = 2895$

$K_1 = 424.6$

By substitution,

$$\frac{0.000586 - 0.000174}{2895 - 4246}$$

Slope of the graph $= \frac{0.00412}{2470.4}$

$$= 1.668x10^{-7}$$

Where: $(swirr)^2 = \frac{B}{K}$

$$(swirr)^2 = \frac{B_2 - B_1}{K_2 - K_2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(15)$$

$$swirr = \sqrt{\frac{B_2 - B_1}{K_2 - K_2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(16)$$

Equating equation (36) and (38), Therefore,

$$swirr = \sqrt{\text{slope of the graph}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots...(17)$$

Where, slope of the graph = 1.668 x 10^{-7} (Fig.25)

$$swirr = \sqrt{1.668 \text{x} 10^{-7}}$$

Swirr = 4.084 x 10^{-4}

= 0.00041

Therefore, graphical determination of irreducible water saturation constant in the study area is 0.00041.

Hence, Dresser Atlas equation of permeability can be written; this can be shown in below:

Recall, dresser atlas equation of permeability:

$$K = \frac{0.136 \times \phi^{4.4}}{(swirr)^2}$$

From the graph, irreducible water saturation constant has been derived, this is 0.00041

Where, swirr = 0.00041

By substitution,

$$K = \frac{0.136 \times \phi^{4.4}}{(0.00041)^2}$$

$$K = \frac{0.136 x \phi^{4.4}}{1.681 x 10^{-7}}$$

K = 809, 042.2x $\phi^{4.4}$ ………………………………………………..(18)

The equation (40) can be approximately as:

K = 8.09 x 10^5 x $\phi^{4.4}$ ....(19)

Therefore, empirical formula between Permeability and Porosity is generated as:

K = 8.09 x 10^5 x $\phi^{4.4}$ ……………………………………........... (20)

DISCUSSION AND CONCLUSION

The reservoirs for the discovered hydrocarbons in the study area are sandstones within the Agbada Formation. Petrophysical evaluation was carried out on the geophysical wireline logs. A total of three hydrocarbon reservoirs were identified and evaluated. The petrophysical parameters of reservoir A range from 32-22%, 5024-116.2md, 20-14% and 86 – 80% for porosity (ø), permeability (K), water saturation (S_w) and hydrocarbon saturation (S_h), respectively. From the Dresser standard, the porosity (ø) ranges from excellent to very good, while the permeability (K) is excellent. Its transmissivity ranges from 50952mdft–648148 mdft.

The petrophysical parameters of the reservoir B range from 30-18%, 1997.8 -166.5md, 30-14% and 86 – 70% for porosity (ø), permeability (K), water saturation (S_w) and hydrocarbon saturation (S_h), respectively. Its transmissivity ranges from 14935 – 87806mdft. From the Dresser standard, the porosity (ø) ranges from very good to good, while its permeability (K) ranges from excellent to good.

The reservoirs bulk volume water (BVW) values calculated are close to constant, this indicates that the reservoir are homogenous and at irreducible water saturation. Therefore, reservoirs can produce water – free hydrocarbon. When a reservoir is at irreducible water saturation, water saturation (S_w) will not move because it is held on grains by capillary pressure. The petrophysical parameters show a gradual decrease from the top to bottom of the wells, reflecting increase in compaction with depth. The porosity, permeability and transmissivity also followed the same trend.

.In reservoir A, both porosity and permeability are excellent while its transmissivity is the highest. The hydrocarbon saturation ranges 86 – 80%. In reservoir B, both porosity and permeability are very good. The hydrocarbon saturation ranges 86-70% while its transmissivity is the second among the three reservoirs.

With these petrophysical values, the reservoirs of the study area can be said to be prolific in terms of hydrocarbon production and they will produce water-free hydrocarbon due to the fact that all these reservoirs are homogenous and at irreducible water saturation.

The quality of the reservoirs in terms of porosity, permeability and transmissivity decreases down the depth. The reservoir A is the best in terms of hydrocarbon production and hydrocarbon in such wells can easily migrate to the wellbore as compared to other one reservoir.

RECOMMENDATION

In the course of this research work, nine empirical formulas relating depth, porosity, permeability, and irreducible water saturation were generated. These equations will serve as a guide to estimate the value of permeability and porosity at various depths.

The formulas between the depth (d) and porosity (∅) are:

(1) $D = 289.52\ \emptyset^{-1}$ Where: D = depth in feet and ∅= Porosity (%)
(2) $D = 88.25\ \emptyset^{-1}$ Where: D = depth in metres

While the formulas between the porosity (∅) and depth (d) can be derived from the equation 1 and 2 as:

(3) $\emptyset = 289.52\ D^{-1}$ Where: D = depth in feet and ∅= Porosity (%)
(4) $\emptyset = 88.25\ D^{-1}$ Where: D = depth in metres

The formulas between the depth (d) and permeability (K) are:

(5) $D = 3.7 \times 10^{6} K^{-1}$ Where: D = depth in feet and K= Permeability (md)
(6) $D = 1.1 \times 10^{6} K^{-1}$ Where: D = depth in metres.

While the formulas between the permeability (K) and depth (d) can be derived from the equation 5 and 6 as:

(7) $K = 3.7 \times 10^{6} D^{-1}$ Where: D = depth in feet and K= Permeability (md)
(8) $K = 1.1 \times 10^{6} D^{-1}$ Where: D = depth in metres.

Therefore, empirical formula between Permeability and Porosity is generated when irreducible water saturation constant is derive can be written as (9) $K = 8.09 \times 10^{5} \times \phi^{4.4}$

CONTRIBUTION TO KNOWLEDGE

This work could be used as reconnaissance tool to pre-determine permeability and porosity at various depths using the empirical formulas generated.Water saturation, irreducible water saturation, porosity, permeability andhydrocarbon saturation combined could be used to give advice on possible locations to drain holes for further field development. This work could also be incorporated into a number of multi-disciplinary projects thatuse integrated subsurface datasets (core, 3D seismic and production data) to further characterize geology and fluid flow in hydrocarbon reservoirs.

REFERENCES

Adeleye, D. (1975). Nigeria Late Cretaceous stratigraphy and paleogeography. American Association of Petroleum Geologist, bulletin p. 2302-2312.

Adeleye, D. and T. Dessauvogie (1970). Stratigraphy of the Niger embayment near Bida, Nigeria African Geol. Ibadan, p. 181-186.

Allix, P. (1983). Environments mesozoiques de la partie nordorientale du fosse de la Benoue, (Nigeria). Stratigraphie–sedimentologies. Evolution geodynamique. Trav. Lab. Sci. Terr., St. Jerome, Marseille France B21, p. 1-200.

Amajor, L. and F . Lebekmo (1990). The Vicking (Albian) Reservoir Sandstones of central and south-centra Alberta, Canada. Part 1 Geometry and Depositional History: Journal of Petroleum Geology 13 (3), p. 315 – 328.

Beka, F. and M. Oti (1995). The distal Offshore Niger Delta: from tier prospects of a mature petroleum province, in, Oti, M.M., and Postina, G., eds., Geology of Deltas: Rotterdam, A.A. Balkema, p. 237-241.

Benkhelil, J. and M. Guiraud (1980). La Benoune (Nigeria): une chaine intracontinentale de style atlasique. C.R. Acad. Sci., Paris 290, p.1517-1520.

Owolabi, O,; Longjohn, T. and J. Ajienka. (1994). An empirical expression for permeability in unconsolidated sands of the eastern Niger Delta, 17: 111-116.

Ozumba, M.; Omene, D. and C. Otoghile (2005). The Opuama channel area 3d prospectivity review impact of high resolution sequence stratigraphy. NAPE Bulletin, vol. 18, No. 1, p. 1-11.

Tenker, S. (1996). Building the 3-D jigsaw puzzle; applications of sequence stratigraphy to 3-D reservoir characterizationof Permaian basin. American Association of Petroleum Geologists, Bulletin, V. 80, p.460 – 485.