Prediction of Reservoir Energy Shale Water Drive in a Reservoir Adjacent to Overpressure Shale: A Case Study of Niger Delta.

S.O. Salufu Ph.D. (in view)[1] and A. Sulaimon Ph.D.[2]

[1]Geophysics Department, Ambrose Alli University, Ekpoma, Nigeria.
[2] Department of Geosciences and Petroleum Engineering, Universiti Teknologi, Petronas, Malaysia.

E-mail: just4samuel@gmail.com*

ABSTRACT

An analytical method was used to develop a model for evaluating performance of a reservoir that is adjacent to overpressure shale base on the assumption that shale compaction resumes when there is disequilibrium in natural pressure due to withdrawal of fluids from reservoir adjacent to overpressure shale for a certain periods. The resumption of shale compaction in overpressure shale is evidence of shale water influx from overpressure shale into adjacent reservoir.

Reservoir data, reservoir fluid data, pressure and rock compressibility of overpressure shale from three offshore wells in the Niger Delta oil field were used to validate the model. The results were compared with field data. The results showed good agreement with field data. The study shows that overpressure shale adjacent to a reservoir contributes additional energy drive and enhances the performance of a reservoir as long there is disequilibrium in natural pressure and reactivation of sealed fractures that are existing within overpressure shale as production commences in the adjacent reservoir. These changes due to production of fluids from reservoir cause shale water influx from overpressure shale to adjacent reservoir and compaction of overpressure shale's pore volume.

(Keywords: overpressure shale, shale water influx, natural pressure disequilibrium, reservoir energy drive, Niger Delta)

INTRODUCTION

Large percentages of reservoirs are located at great depths where overpressure shale prominently occurs (Rehm, 1972 and Martin, 1972). The occurrence of overpressure shale close to a reservoir contributes appreciably to reservoir energy whenever shale water influx resumes (Wallace, 1969 and Chierici et al; 1978). As a result of this, it is very important to predict future occurrence of shale water influx in reservoirs that are located close to overpressure shale, in order to evaluate future performance of a reservoir.

Chierici et al. (1978) developed a numerical model to predict shale water drive in sand formations with randomly interbedded, thin, discontinuous shale layers. However, the model cannot predict shale water influx in overpressure shale that overlies, underlies, or lies beside a reservoir.

Similarly, Fertl and Timko (1970) used two pulse-neutron logs that were run a year apart to monitor shale water influx in reservoirs adjacent to over pressure shale bodies which are being produced in several wells. He noticed that there were sigma value changes in the sand due to increase in water saturation and also noted changes in sigma decrease due to compaction and porosity decrease in the adjacent shale bodies. The limitations of this method are its inability to predict shale water influx and quantitative rate of shale water influx.

However, this present study is aimed at; (1) Predicting shale water influx in reservoirs that are overlain by overpressure shale, underlain by overpressure shale, or reservoir that are beside overpressure shale due to lateral change in facies; (2) to predict shale water influx quantitatively and rate of shale water influx; and (3) to use the results from 1 and 2 to determine whether shale water influx contributes additional reservoir energy drive.

MATERIAL AND METHODS

An analytical method was used to develop a simple model using Darcy's equation of flow in porous media; permeability modulus; and rock compressibility based on the principle that shale water compaction may resume when there is disequilibrium in natural pressure by withdrawal of fluids from the reservoir for a certain period; and there is pressure differential across shale/sand interface due to production of hydrocarbon from reservoir adjacent to overpressure shale. Data from offshore oil field in Niger Delta was used to validate the model.

It is assumed that overpressure shale is fractured and the fractures are sealed before natural disequilibrium commenced, and the commencement of natural disequilibrium by stress induction resulting from production of hydrocarbon from adjacent reservoir, reactivates the existing sealed fractures within the overpressure shale. Thus, causes shale water to flow from overpressure shale into adjacent reservoir (Figure 1). The flow is assumed to be linear and laminar.

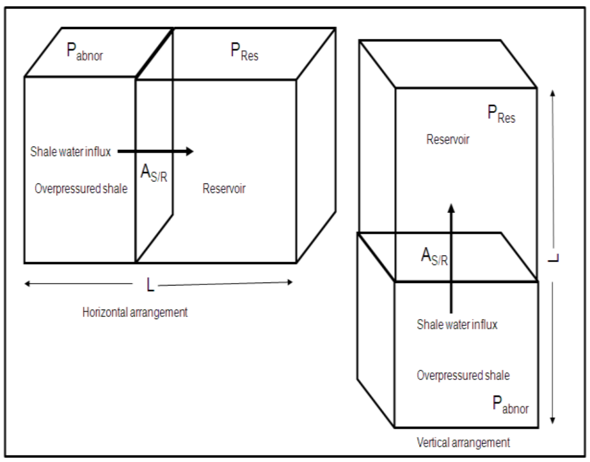


Figure 1: Diagrammatic Illustration of Shale Water Influx.

Zhang and Ambastha (1994) and Qin and Zhang (1994) related permeability modulus with pressure drop and permeability as:

$$\alpha_{\kappa} = -\frac{1}{K}\frac{\partial k}{\partial p} \quad \textbf{(1)}$$

According to Holt (1989); and Luo and Feng (2009), the permeability modulus of rock is related to rock compressibility.

Therefore:

$$\alpha_{\kappa} = C_f = -\frac{1}{K}\frac{\partial k}{\partial p} \quad \textbf{(2)}$$

Relating shale compressibility with shale permeability:

$$C_f \partial p = \frac{-1}{K}\partial k \quad \textbf{(3)}$$

Integration:

$$C_f \int_{P_{abnori}}^{P_{abnor}} \partial p = \int_{K_{abnori}}^{K_{abnor}} \frac{\partial K}{K} \quad \textbf{(4)}$$

$$C_f \left(P_{abnor} - P_{abnori}\right) = In\left(\frac{K_{abnor}}{K_{abnori}}\right) \quad \textbf{(5)}$$

$$K_{abnor} = K_{abnori}\ell^{c_f\left(P_{abnor}-P_{abnori}\right)} \quad \textbf{(6)}$$

Since $\ell^x = 1 + x + \frac{x^2}{2} + \ldots$ therefore Eq. (5) becomes:

$$K_{abnor} = K_{abnori}\left[\left(1 + C_f\left(P_{abnor} - P_{abnori}\right)\right)\right] \quad \textbf{(6)}$$

According to Darcy's equation of flow through a porous media, flow rate is given by:

$$q = -\frac{KA}{\mu}\frac{\partial P}{\partial l} \quad \textbf{(7)}$$

Eq. (7) can be modified to express the rate of shale water influx with assumption that there are faults or fractures within the shale which are sealed but the stress of pressure disequilibrium reactivates them:

$$q_{shaw} = \frac{-K_{abnor}A_{S/R}\partial P}{\mu_{shaw}\partial L} \quad \textbf{(8)}$$

$$q_{shaw}\, dL = \frac{-K_{abnor} A_{s/R}}{\mu_{shaw}} \partial p \qquad \textbf{(9)}$$

Integrating Eq. (9) yields:

$$q_{shaw} \int_{O}^{L} \partial L = \frac{-K_{abnor} A_{s/R}}{\mu_{shaw}} \int_{P_{abnor}}^{P_{res}} \partial p \qquad \textbf{(10)}$$

$$q_{shaw} L = \frac{-K_{deq} A_{s/R} (P_{res} - P_{abnor})}{\mu_{shaw}} \qquad \textbf{(11)}$$

$$q_{shaw} = \frac{K_{abnor} A_{s/R} (P_{abnor} - P_{res})}{\mu_{shaw} L} \qquad \textbf{(12)}$$

Combining Eq. (6) and Eq. (12) with assumption that flow from overpressure shale into the reservoir is linear and laminar.

$$q_{shaw} = \frac{K_{abnori} \left[(1 + C_f (P_{abnor} - P_{abnori})) \right] A_{s/R} (P_{abnor} - P_{res})}{\mu_{shaw} L} \qquad \textbf{(13)}$$

Equation (13) can be further written as:

$$q_{shaw} = C \lambda \qquad \textbf{(14)}$$

Where,

$$\lambda = \frac{(P_{abnor} - P_{res})}{\mu_{shaw} L} \quad \text{(psi/(cp.ft))}$$

$$C = K_{abnori} \left[(1 + Cf (P_{abnor} - P_{abnori})) \right] A_{s/R}$$
(md/ft^2)

Equation (14) can be used to predict if there is water influx or not from overpressure shale into the adjacent reservoir as additional reservoir energy drive by simply computing q_{shaw}, λ, and C for a given range of time and plot q_{shaw} against λ.

RESULTS AND DISCUSSION

The model was validated using reservoir data, permeability, shale compressibility, shale water viscosity, and pressure, from three offshore reservoirs in the Niger Delta. Table 1 shows values of the input and predicted parameters (t (time), c_f (rock compressibility), μ_{shaw} (shale water viscosity), λ (Pressure difference per length), C (C constant), $A_{S/R}$ (Cross sectional area of shale/sand interface, L (total length of overpressure shale and reservoir), k_{abnor} (permeability at abnormal pressure after disequilibrium of natural pressure), P_{abnor} (abnormal pressure at a given period after disequilibrium of natural pressure), P_{res} (reservoir pressure), and q_{shaw} (shale water flow rate) for diagnosing shale water influx while Figure 2 show diagnostic plots for predicting occurrence of water influx from overpressure shale into the adjacent reservoir.

The slope of diagnostic plot for shale water influx for reservoir X and Y, 177564md/ft^2 and 261704md/ft^2 respectively (See Figures 2a and 2b) are values lower than the value of C at initial year of occurrence of P_{abnori} (Table 1).This indicates reduction in pore volume due to fluid migration. This shows that water influx occurred within 5242ft and 5622ft for reservoir X and within 3311ft and 4467ft for reservoir Y. The year at which the water influx commenced in reservoir X and Y corresponds to the field observation. However, Figure 2c shows that the slope value remains (2-14) the same with the value of C at the initial year of P_{abnori} (Table 1) which also agrees with the field observation. Therefore, there was no compaction in pore volume of the overpressure shale since there was no fluid migration from overpressure shale into the reservoir. This indicates that there was no shale water influx in reservoir Z since pressure disequilibrium has not occurred. Consequently, the overpressure shale was not fractured or fractured and sealed before the commencement of natural disequilibrium.

Reservoir X had early shale water influx as from the second year of gas production which caused early disequilibrium in the natural pressure in the reservoir pressure and pressure at overpressure shale adjacent to the reservoir. The change in the initial value of C from 180000md/ft^2 to 178628.7md/ft^2 in the second year (Table 1) indicates inception of shale water influx.

Table 1: Input Data and Predicted Parameters for the Shale Water Influx.

Reservoir	t (yr)	Pabnor(Psi)	Pres(Psi)	k (md)	q(bbl/yr)	λ/(Psi.cp.ft)	C(md/ft²)
Reservoir X	1	2887	2500	200	103419.2	0.574551	180000
	2	2700	2450	198.4763	66299.33	0.371157	178628.7
	3	2600	2350	197.6615	66027.15	0.371157	177895.4
	4	2550	2300	197.2541	65891.06	0.371157	177528.7
	5	2400	2250	196.0319	39289.68	0.222694	176428.7
	6	2350	2150	195.6245	52277.37	0.296926	176062.1
	7	2300	2100	195.2171	52168.5	0.296926	175695.4
	8	2200	2000	194.4023	51950.76	0.296926	174962.1
	9	2150	1900	193.9949	64802.36	0.371157	174595.4
			AS/R=900ft2	µshaw=0.303cp	L=2223ft	cf=40.74E-6Psi-1	
Reservoir Y	1	4075	3500	350	140272.3	0.534371	262500
	2	4075	3200	350	213457.9	0.813173	262500
	3	4075	3000	350	262248.2	0.999041	262500
	4	4075	2900	350	286643.4	1.091975	262500
	5	4070	2790	350	312258.4	1.189556	262500
	6	3500	2650	345.9746	204974.2	0.789939	259480.9
	7	3150	2500	343.5244	155634.9	0.604071	257643.3
	8	2700	2400	340.374	71172.75	0.278802	255280.5
	9	2500	2300	338.9739	47253.32	0.185868	254230.4
			AS/R=750ft2	µshaw=0.391cp	L=2752ft	cf=20.002E-6Psi-1	
Reservoir Z	1	2887	2500	450	542309.8	0.964106	562500
	2	2887	2150	450	1032771	1.836037	562500
	3	2887	1950	450	1313034	2.334283	562500
	4	2887	1800	450	1523232	2.707968	562500
	5	2887	1750	450	1593298	2.832529	562500
	6	2887	1600	450	1803495	3.206214	562500
	7	2887	1450	450	2013693	3.579899	562500
	8	2887	1300	450	2223891	3.953583	562500
	9	2887	1250	450	2293957	4.078145	562500
			AS/R=1250ft2	µshaw=0.392cp	L=1024ft	cf=52.74E-6Psi-1	

This observation is similar to field observation (Figure 3); the sigma value began to increase in the second year in the reservoir (R) which indicates increase in water saturation as a result of shale water influx from compacted overpressure shale. While there is decrease in sigma value of the overpressure shale (OS) in the second year due to increase in compaction and decrease in porosity, indicating decrease in water saturation in the overpressure shale.

There was delay in shale water influx in reservoir Y until the sixth year due to the fact that natural pressure has not attained disequilibrium as shown in Table 1. From the second year to the fifth year, the values of C were constant throughout with the value of C at P_{abnori} until the sixth year when the values of C began to fall down below the initial value at P_{abnori}. This reduction in C values reflects compaction in pore volume of overpressure shale due to influx of water from the overpressure shale into the adjacent reservoir. This observation is similar to the field observation (Figure 4); the values of sigma were all constant from the first year to the fifth year until it started to increase at the reservoir (R) while it began to decrease at overpressure shale (OS). This indicates that there was no water influx from the first year to the fifth year but as from the sixth year, water influx began.

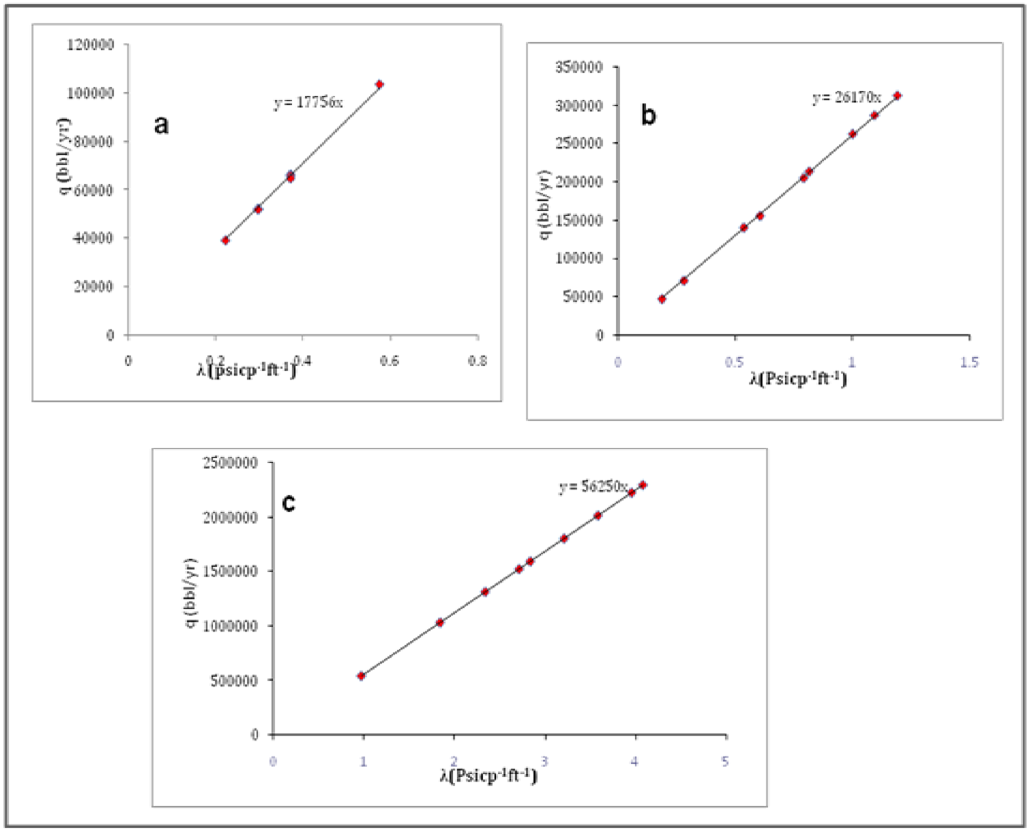
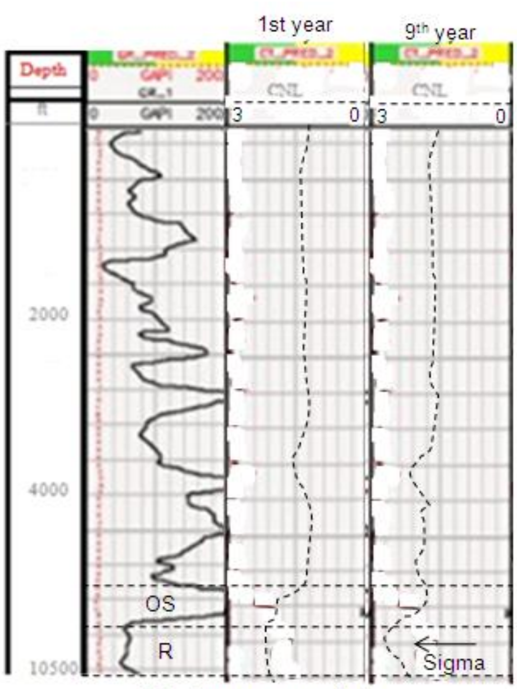


Figure 2: Diagnostic Plot for Shale Water Influx. A) Reservoir X, B) Reservoir Y, C) Reservoir Z.



OS - Overpressure shale
R - Reservoir

Figure 3: Pulsed Neutron Logs Run after Completion of Well A in Reservoir X.

OS - Overpressure shale
R - Reservoir

Figure 4: Pulsed Neutron Logs Run after Completion of Well B in Reservoir Y.

There is constant trend in the value of C from the first year to the ninth year in the history of hydrocarbon production from the reservoir Z. This indicates non-occurrence of shale water influx due to non-reduction in pore volume of the overpressure shale. Reason for no reduction in the pore volume of the over pressure shale is simply because there was no yet disequilibrium in natural pressure existing between the overpressure shale and the adjacent reservoir Z of which has not allowed fluid migration from overpressure shale unit into the reservoir Z.

It would be noticed that the values of C from the first year to the ninth year was constant in reservoir Z from the first year of hydrocarbon production to the ninth year which suggests that there was no shale water influx. This does not mean that there can be no water influx from elsewhere apart from shale water, but the field data indicates increase in the sigma value to right in the ninth year in the reservoir (R) while that of overpressure shale (OS) remains constant after the commencement of production (Figure 5).

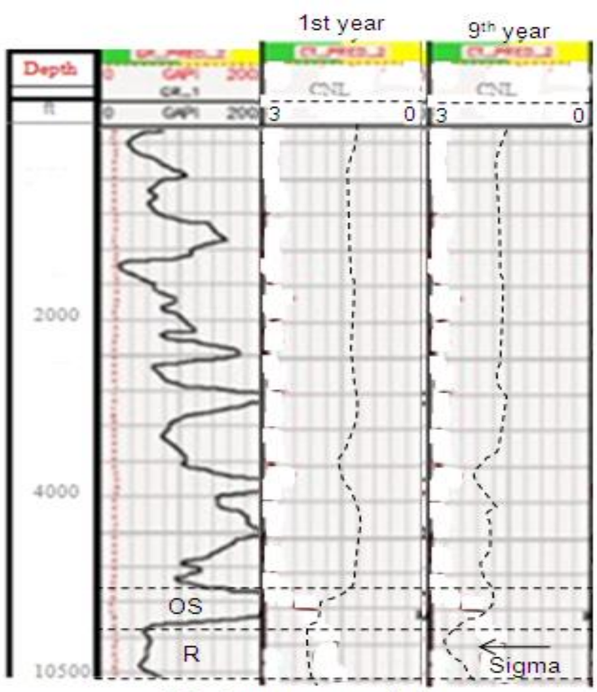


Figure 5: Pulsed Neutron Logs Run after Completion of Well C in Reservoir Z.

This observation suggests that the water influx is solely from adjacent aquifer that is, not from overpressure shale. However, this model can only predict shale water influx from overpressure shale not water influx from aquifer. In order to be able to identify if there is water influx from aquifer in a reservoir that shows that there is no shale water influx like reservoir Z, then one will have to use the conventional material balance method to ascertain water influx from aquifer.

CONCLUSION

A model for predicting shale water influx from overpressure shale into adjacent reservoir has been developed. The model uses the principle of compaction concept. It requires rock compressibility, pore pressure of overpressure shale, reservoir pressure, permeability, cross sectional area, shale water viscosity, reservoir pressure, and total thickness of overpressure shale and reservoir.

The proposed model has been successfully validated with well data and reservoir data from The Niger Delta offshore field. The major success of this present model over the method of Fertl and Timko (1970) is that it can give estimated quantity of shale water that has migrated from overpressure shale to adjacent reservoir. The model can also estimate the rate of shale water influx, the pressure difference in overpressure shale and adjacent reservoir, and the degree of compaction of overpressure shale. Furthermore, it can predict future performance of the reservoir from the first year of natural pressure disequilibrium. It can predict shale water influx in reservoirs that are overlain or underlain by overpressure shale, and reservoirs that are beside overpressure shale due to lateral change in facies unlike Chierici et al. (1978) model that only predicts shale water influx in reservoirs with discontinuous, thin, interbedded shale layers.

Nomenclature

C_f = Rock compressibility (psi^{-1})

ϕe_{ff} = Effective porosity

$\partial P =$ Pressure change

$\partial k =$ Shale permeability change

$\alpha_{\kappa} =$ Permeability modulus

$k =$ Shale permeability (md)

$q_{shaw} =$ Shale water flow rate (bbl/yr)

$P_{res} =$ Reservoir pressure (psi)

C = C constant

$A_{S/R} =$ Cross sectional area shale/sand interface (ft^2)

$\mu_{shaw} =$ Shale water viscosity (md/ft^2)

$C_{P_{abnori}}$ = Value of C at period of initial abnormal pressure (md/ft^2)

$C_{P_{abnor}}$ = Value of C at period of a given abnormal pressure (md/ft^2)

$P_{abnor} =$ Abnormal pressure at a given period after disequilibrium of natural pressure (psi)

$P_{abnori} =$ Initial abnormal pressure before disequilibrium of natural pressure (psi)

$k_{abnor} =$ Permeability at abnormal pressure of a given period after disequilibrium of natural pressure (md)

$k_{abnori} =$ Permeability at initial abnormal pressure before disequilibrium of natural pressure (md)

$L =$ Total length of shale and reservoir in direction of shale water flow (ft)

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ABOUT THE AUTHORS

Samuel Obomheile Salufu is a Lecturer in the Department of Geophysics, Ambrose Alli University, Ekpoma, Edo State, Nigeria. He is a registered Geologist and Petroleum Engineer with Council of Nigerian Mining Engineers and Geoscientists (COMEG), a member of the Nigerian Mining and Geosciences Society (NMGS) and Society of Petroleum Engineers (SPE). He is currently running is Doctoral degree on Marginal Field Development in the Department of Petroleum Engineering, University of Ibadan, Ibadan, Nigeria. His research interests are in

Reservoir studies, Reservoir management, flow assurance, Basin analysis, and Environmental studies

Dr. A. Sulaimon, is a Senior Lecturer in the Department of Geosciences and Petroleum Engineering, Universiti Teknologi, Petronas, Malaysia. He obtained his B.Sc., M.Sc., and Ph.D. in Petroleum Engineering.

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