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PREDICTION OF RESERVOIR CHARACTERISTICS IN WESTERN GHANA OILFIELD (TANO BASIN)

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Abstract

The Tano Basin is one of the prospective oil fields in Western part of Ghana. Geographically, the area lies 4°46′ north of latitude and about 3° west of longitude. The study dwells on the evaluation of the Petrophysical parameters of the reservoir through the modification of the extended Archie's model by Pickett. Through the technique, the reservoir Petrophysical parameters such as specific surface per unit volume, permeability, capillary pressure, bulk volume and height above free water surface have been established. The procedure uses existing resistivity model which is a function of water saturation and porosity. Resistivity is expressed as an additional function of permeability, specific surface per unit volume, capillary pressure, bulk volume and height above free water surface through the embedded water saturation model. Additionally, saturation exponent *n,* porosity exponent *m* and tortuosity factor *a* were evaluated in the process. The study presents a useful model of the extended Archie's model which provides a quick integration of formation Petrophysical parameters which is very significant for reservoir interpretation, prognostication and appraisal

Keywords: *Tortuosity; water saturation; Capillary pressure; Resistivity; Porosity; permeability.*

1. Introduction

Hydrocarbon reserves inundation is a key function in formation estimation and by large extent reserves capacity evaluation. It equally offers a lead variable in reservoir formation development and modeling. Several characteristics are employed in the evaluation of reservoirs and reserve inundation. These include water saturation, porosity, permeability, specific surface per unit volume, capillary pressure, height above free surface and bulk volume. Pickett plot presents a log-log relationship between porosity and resistivity [1]. The Petrophysical parameters indicated above are superimposed via the Pickett plot and determination of reservoir parameters of the six exploratory well in the Western Tano Basin are established. Sanyal and Ellithorpe [2] showed that Pickett plot which is combines the Archie's models results in a linear plot with the slope representing porosity exponent (m). The study presents a well work out plot embracing all the Petrophysical parameters such as water saturation, porosity, permeability, specific surface per unit volume, capillary pressure, height above free surface and bulk volume in a single plot. The combination of these parameters in a single plots presents one time simplified important information for evaluation of the reservoir.

2. Study area

In this study, three wells namely 1S-1X, 1S-3AS, 1S-4AX, ST-05, ST-06 and ST-7H were studied, Fig1. The studied wells are located in the Western Basin (Tano Basin), a sub-basin of Cape Three Point. It forms part of the larger Ivory Coast Basin in the Gulf of Guinea of West Africa. Geographically, the area lies 4°46′ north of latitude and about 3° west of longitude, east-west onshore-offshore structural basin [3]. It is precisely 35km offshore of Ghana and occupies about 3000km^2 Figure 1.

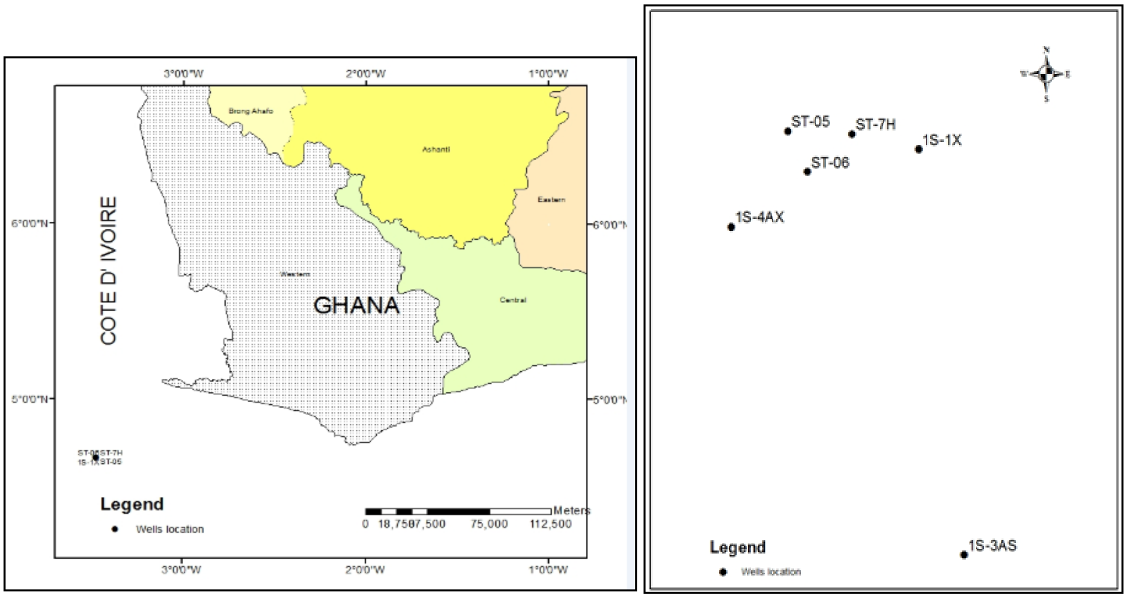


Figure 1. Location of studied wells

3. Theory of resistivity model

As mentioned earlier, cementation factor, *m,* saturation exponent, *n,* and tortousity factor, *a,* are key variables in the Archie's model. A conservative value of 2 has been assumed for cementation factor. For saturation exponent, it is reported in literature to be between 2 (strongly water-wet rocks) and 25 (strongly oil-wet rocks) [4]. A value of unity is usually assume for tortuosity, *a.* It is certain that wrong assumption of these variables has an effect on the reliability of the saturation estimates. Archie's model was initiated based on two experimental connections where resistivity index *(RI)* and formation factor (*F).* The resistivity index and formation factor are expressed as in Equation 1 and 2

$$RI = \frac{R_t}{R_o} = \frac{1}{S_w^n} \quad (1)$$

$$F = \frac{R_o}{R_w} = \frac{a}{\emptyset^m} \quad (2)$$

where, *Rt* is the true resistivity of the rock saturated with both formation water and hydrocarbons; *Ro* is the resistivity of a 100% water (brine)-saturated sandstone; S_w water saturation in fraction and *n* is the saturation exponent, R_w is the water (brine) resistivity; and *m* is the cementation factor, *a* is a tortuosity factor, ∅ rock prosity in fraction.

Combination of Eqs. (1), and (2) leads to Eq. (3)

$$S_w = \left(\frac{1}{RI}\right)^{\frac{1}{n}} = \left(\frac{F \times R_w}{R_t}\right)^{\frac{1}{n}} \quad (3)$$

Rearranging Eq. (3) gives expression to true resistivity

$$R_t = a \times \emptyset^{-m} \times R_w \times S_w^{-n} \quad (4)$$

Applying logarithm rules to Eq. 4 yields (7);

$$logR_t = \log(aR_w) - mlog\emptyset - nlogS_w \quad (5)$$

This is the theory underlying the Pickett's plot. Eq. (5) leads to a straight line plotting on a log-log paper with a slope of (-m). The slope is determined by measuring distance on the Rt axis and expressing as a ratio of corresponding distance on porosity axis [5]. The intercept at where porosity axis equals to unity corresponds to (aR_w) which lends to detthe ermination of *a* when R_w is known and vice versa. According to Pickett [6] saturation exponent, *n*, approximates porosity exponent, *m*. since no data on water resistivity at the study area was available, an apparent water resistivity R_{wa} was estimated. Additionally, Winsaurer [7] evaluated the formation factors and porosities on some 29 sandstones of North America. They concluded that for rocks studied, an expression of the form Eq. 2 described their experimental work.

They evaluated tortuosity *a* and cementation *m* to be o.62 and 2.15 respectively. Since Tano Basin, the study area is sandstone formation the tortuosity value of 0.62 was adopted for this work. Figure 2 presents the Pickett plots for the six exploratory wells of the Western Tano Basin as an instance. The resultant Petrophysical exponents for the geological domain for all the exploratory wells are equally determined in Table 1.

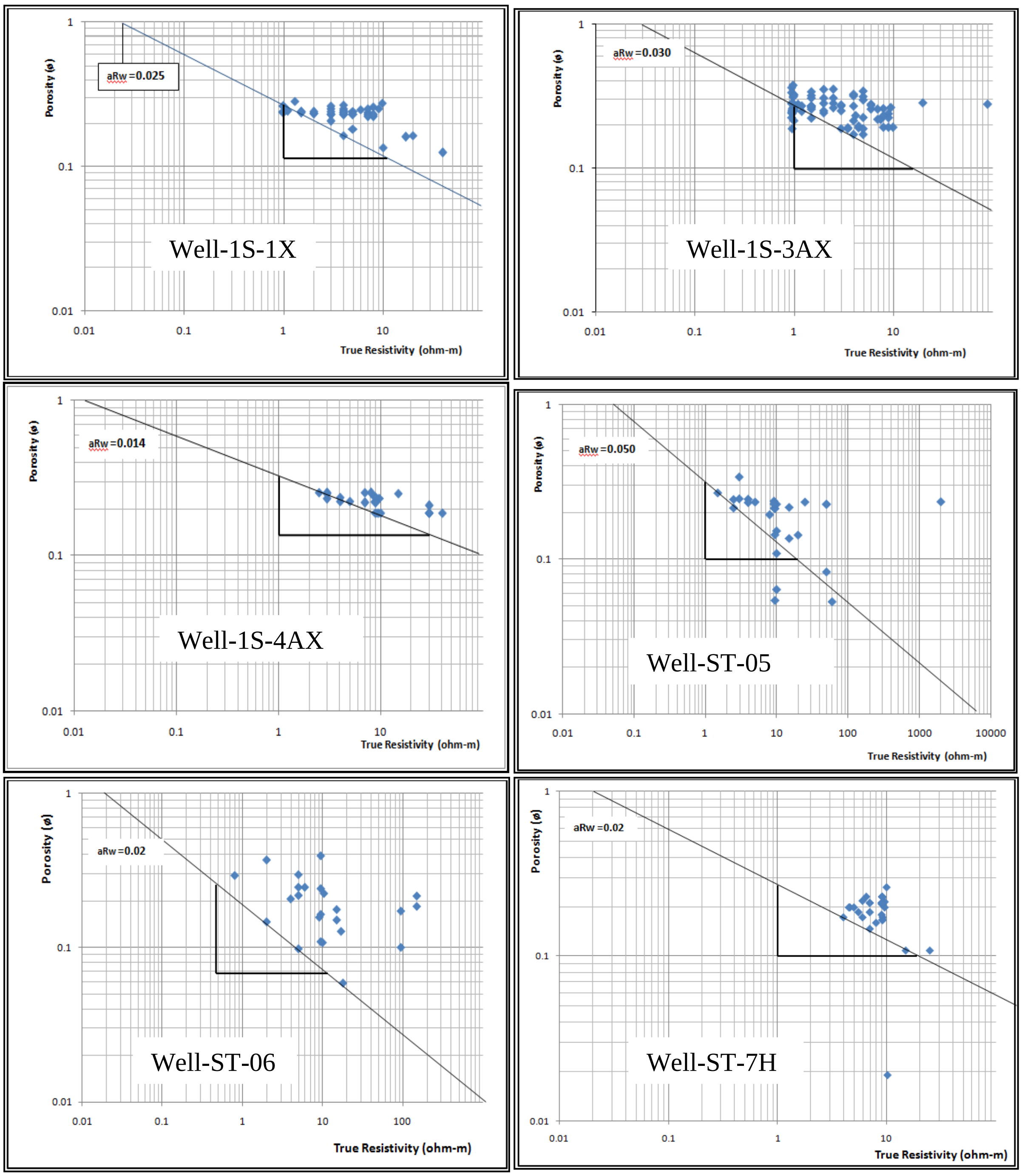


Figure 2. Pickett's plot for the exploratory wells in the western Tano Formation

Table 1. Petrophysical exponents and characteristics of the Western Tano Basin

Well name	aR_w	R_{wa}	m	Δ of S_w	Δ of S_v	Δ of K	Δ of P_c	Δ of B_{VW}
1S-1X	0.025	0.040	1.93	0.52	-4.83	-7.72	3.50	0.00
1S-3AS	0.030	0.048	1.94	0.52	-4.85	-7.76	3.52	0.00
1S-4AS	0.014	0.023	2.69	0.37	-6.73	-10.76	4.88	0.00
ST-05	0.050	0.081	1.21	0.89	-3.03	-4.84	2.19	0.00
ST-06	0.02	0.032	1.36	0.74	-3.40	-5.44	2.47	0.00
ST-07	0.02	0.032	1.97	0.51	-4.93	-7.88	3.57	0.00

3.1. Effect of specific surface per unit solid volume on Archie model

The specific surface of a porous material is the total area exposed within the pore space per unit volume. The unit volume may be the solid material framework, in which case the specific surface is represented by S_v. The specific surface is a key Petrophysical parameter for an understanding of the physics and relationships of porous media. Many practical models have been developed to relate relative permeability with porosity and specific surface of the porous material. One such empirical model is one developed by Kozeny and Carman [8].

$$K = \frac{\emptyset^3}{f \times a \times {S_v}^2} \tag{6}$$

where *f* is the shape factor, *a* is the tortuosity and *Sv* is the specific surface per unit surface area to rock volume.

Morris and Biggs [9] also developed an empirical equation to relate permeability as a function of porosity and irreducible water saturation.

$$K = \left(250 \frac{\emptyset^3}{S_{wir}}\right)^2 \tag{7}$$

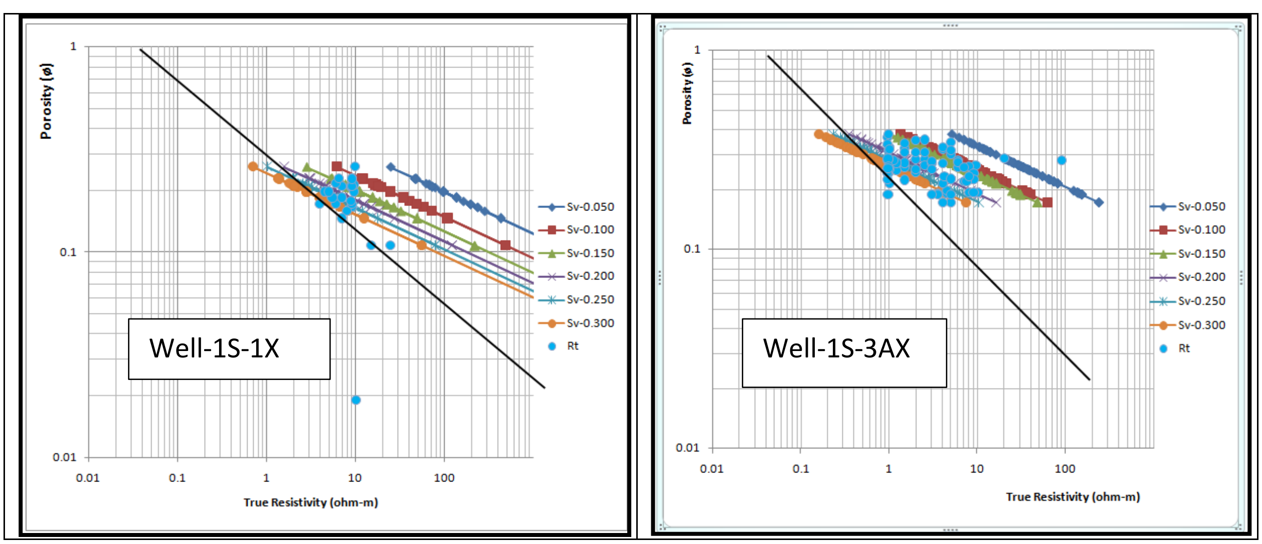
Equating Eq. (6) and (7) leads to an expression for irreducible water saturation

$$S_{wir} = \left(250 \times \emptyset^{\;3} \times {S_v}^2 \times f \times a\;\right)^{1/2} \tag{8}$$

Substituting Eq. 8 into Eq. 4 yields

$$R_t = a \times \emptyset^{-m-1.5n} \times R_w \times \left(250 \times {S_v}^2 \times f \times a\right)^{-0.5n} \tag{9}$$

By plotting R_t against Ø on a log-log coordinate using Eq. (9) should generate straight line with a slope equal to *(- m-1.5n)* with constant specific surface per unit solid volume. Parallel lines of constant specific surface per unit solid volume Eq. (9) are determined via the determination of R_t and the resultant plots are shown in Figure 3 incorporating the specific surface from 0.050 to 0.30.



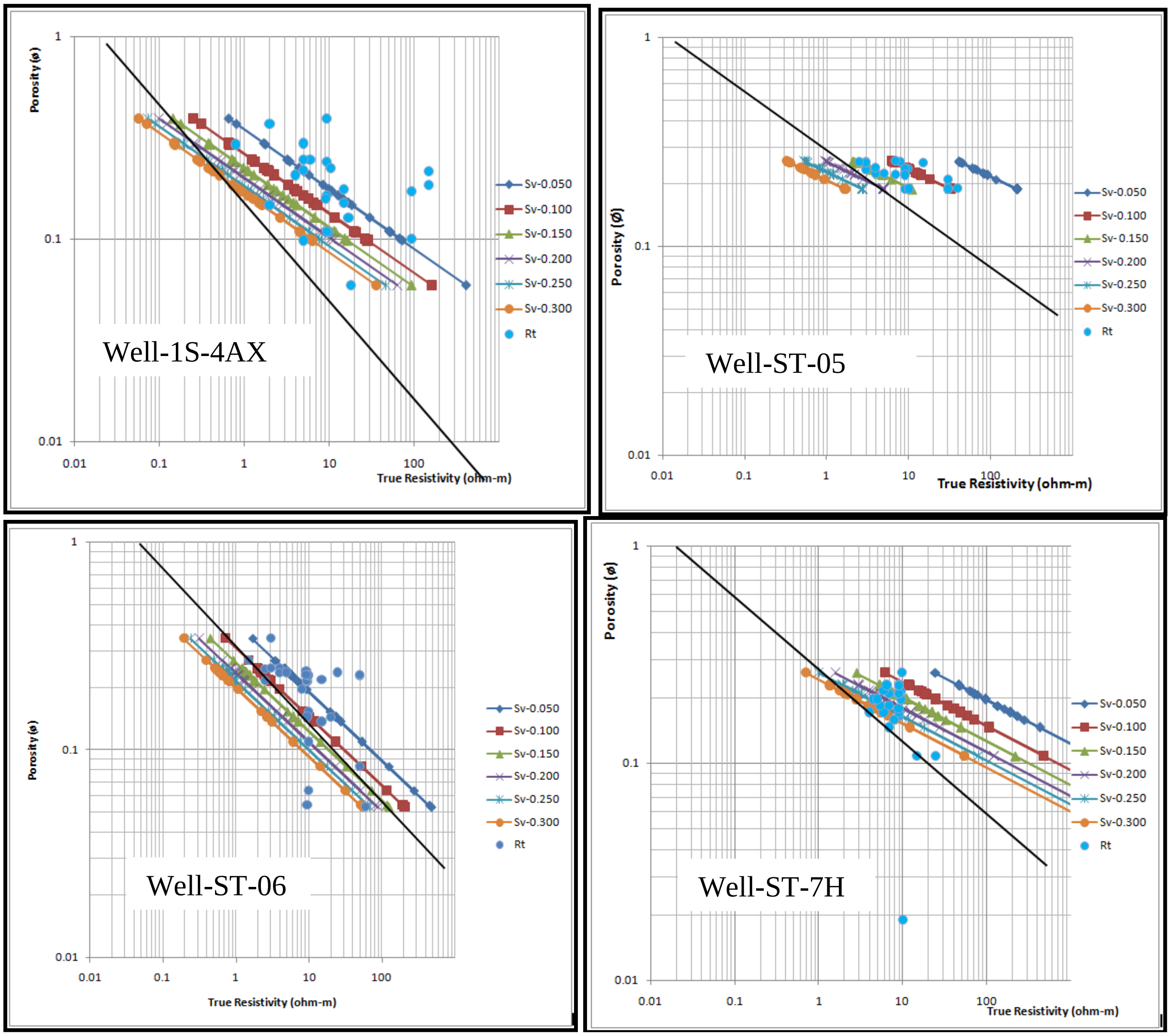


Figure 3. Pickett's plot for the exploratory wells in the western Tano Formation integrated with the specific surface

3.2. Effect of permeability on Archie Model

Permeability is an important Petrophysical parameter which indicates the reservoirs ability to allow fluid to pass through the effective voids. The effect of permeability on the model was investigated. According to Wyllie and Rose [10], permeability is a direct function of porosity and inversely related to irreducible water saturation, Eq. 10.

$$K = \left(250\,\frac{\emptyset^3}{S_{wir}}\right)^2 \qquad (10)$$

$$S_{wir} = \left(250\,\frac{\emptyset^3}{K^{1/2}}\right) \qquad (11)$$

According to El-Khadrgy *et al.* [5], the irreducible water saturation (S_{wir}) relates to the water saturation (S_w) as shown in Eq. 12.

$$S_{wir} = \frac{\emptyset_t \times S_w}{\emptyset_{eff}} \qquad (12)$$

Incorporating Eq. 12 into Eq. 4 yields

$$R_t = a \times \emptyset^{-3n-m} \times R_w \times \left(\frac{250}{K^{1/2}}\right)^{-n} \qquad (13)$$

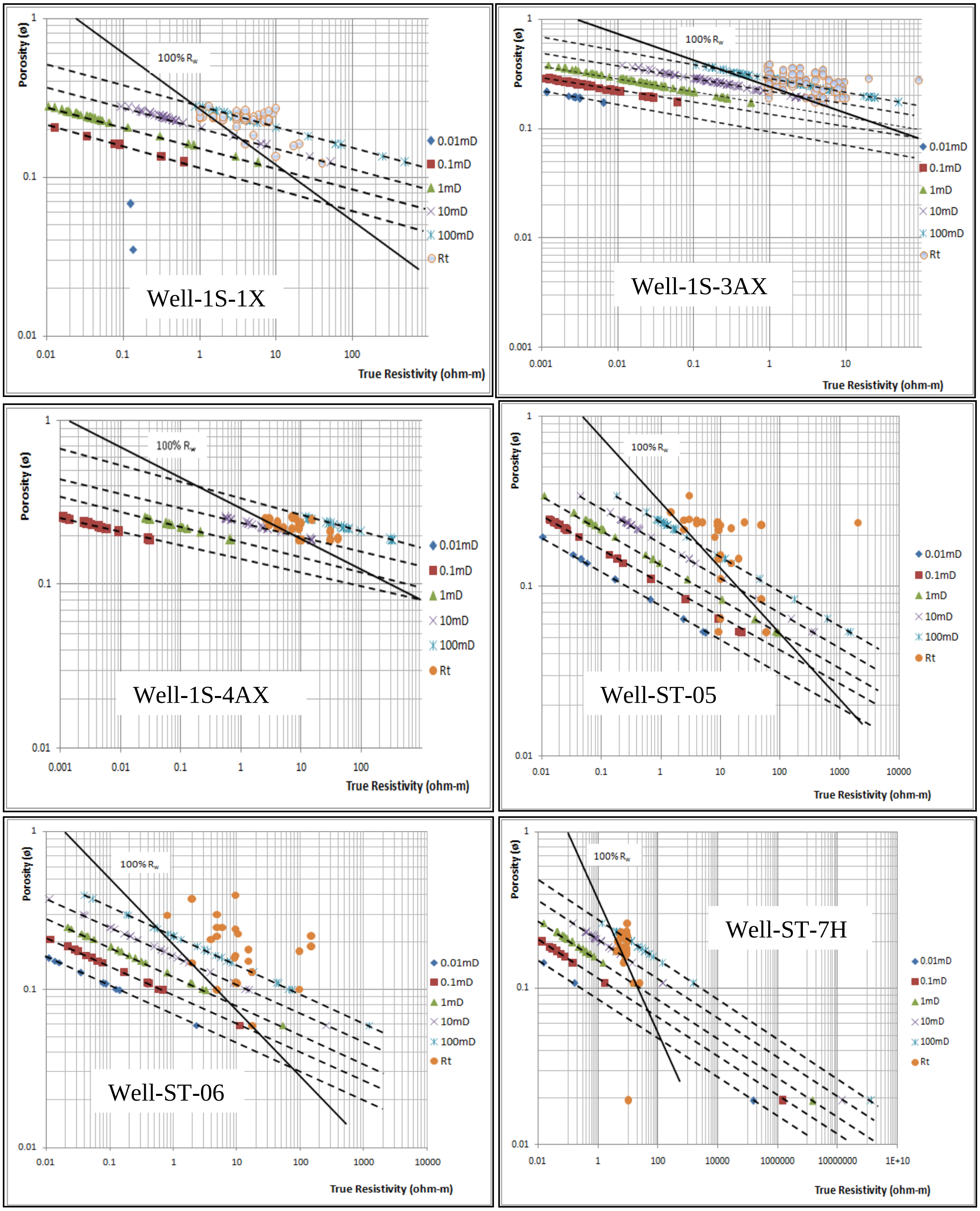


Figure 4. Pickett's plot for the exploratory wells in the western Tano Formation integrated with permeability

Applying logarithm to both sides gives

$$logR_t = (-3n - m) \times log\emptyset + log\left[aR_w \times \left(\frac{250}{K^{1/2}}\right)^{-n}\right] \tag{14}$$

Plotting R_t against Ø on a log-log coordinates results in a linear relation with the slope equal to (-3n - m) with permeability been constant. Parallel permeability lines of different permeability values are drawn using Eq. 13 with the intercept on the true porosity line representing *(aRw (250/K$^{1/2}$)$^{-n}$)* Figure 4 shows the effect of permeability from 0.01 to 100md.

3.3. Effect of capillary pressure on Archie model

The equally important Petrophysical parameter in the characterization of the reservoir is capillary pressure. It is the measure of the pressure difference between two different fluids at equilibrium. Know, and Pickett's [11] generated a model for capillary pressure as a function of rock permeability and porosity as in Eq. 15.

$$P_c = A\left(\frac{K}{1000\emptyset}\right)^{-B} \quad (15)$$

Know, and Pickett's [11] found out that for most rocks *A*is a constant and lies between 151.35 and 22.91. It was also found out that for *B* is approximately 0.45.A further correlation of *A* against water saturation (Sw) approximates Eq. 16.

$$A = 19.5\mathrm{Sw}^{-1.7} \quad (16)$$

Combining Eq. 10, Eq. 16 and Eq. 15 yields Eq. 17:

$$P_c = 3.033(\mathrm{Sw}^{-0.8} \times \emptyset^{-2.25}) \quad (17)$$

Rearranging Eq. 17 gives an expression for water saturation (S_w),Eq. 18:

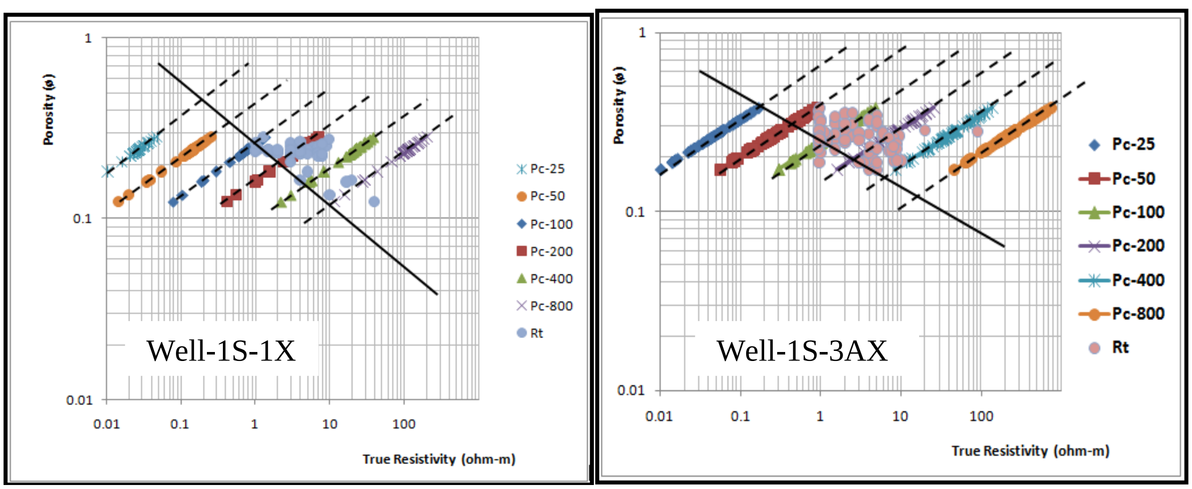
$$\mathrm{Sw} = \left(\frac{P_c}{3.033\times\emptyset^{-2.25}}\right)^{-1.25} \quad (18)$$

Substituting Eq. 18 into Eq. 4 and applying logarithm to both sides

$$R_t = a \times \emptyset^{2.8125n-m} \times R_w \times \left[\left(\frac{P_c}{3.033}\right)^{-1.25}\right]^{-n} \quad (19)$$

$$logR_t = (2.8125n - m) \times log\emptyset + log\left[aR_w \times \left(4.0026 \times P_c^{-1.25}\right)^{-n}\right] \quad (20)$$

Plotting Eq. 19 on a log-log coordinate with a constant *(aR_w)* and varying capillary pressures leads to a linear relationship with a slope equal to $(2.8125n - m)$ and the intercept on the true porosity line represents$\left[aR_w \times \left(4.0026 \times P_c^{-1.25}\right)^{-n}\right]$. Figure 5 shows the effect of constant capillary pressure values from 25 psi to 800 psi incorporated into the model.



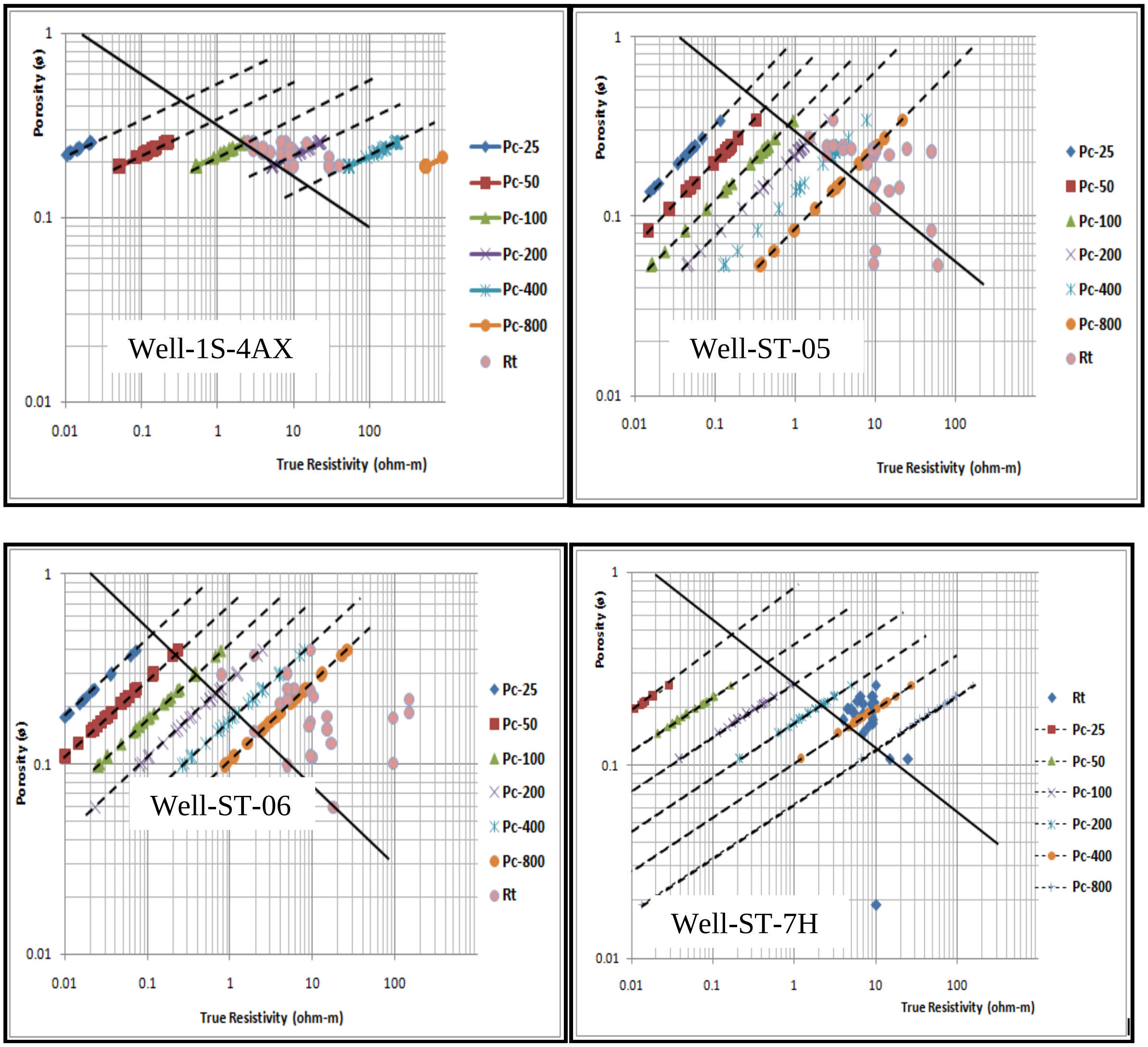


Figure 5. Pickett's plot for the exploratory wells in the western Tano Formation integrated with capillary pressure

3.4. Effect of bulk volume of water

The volume per unit mass of a dry material plus the volume of the air between its particles is referred to as a bulk volume. It is expressed as the product of formation water saturation (S_w) and its porosity (Ø).

$$B_{vw} = S_w \times \emptyset \tag{21}$$

$$S_w = \frac{B_{vw}}{\emptyset} \tag{22}$$

Substituting Eq. 22 into Eq. 4

$$R_t = a \times \emptyset^{n-m} \times R_w \times (B_{vw})^{-n} \tag{23}$$

According to Sanyal and Ellithorpe [2], log-log plots of R_t and Ø produces straight lines with slope equal to *(n-m)* which is also corroborated by both Doveton *et al.* [12] and Buckles [13]. Figure 6 illustrates the effect of bulk volume of water on Archie's model. The plots have zero slope this is due to the fact that *n* is equal to *m* as explained earlier. Hence *(n-m)* is equal to zero leading to vertical lines. The intercept of the vertical on the true porosity plot correspond to $[aR_w \times (B_{vw})^{-n}]$.

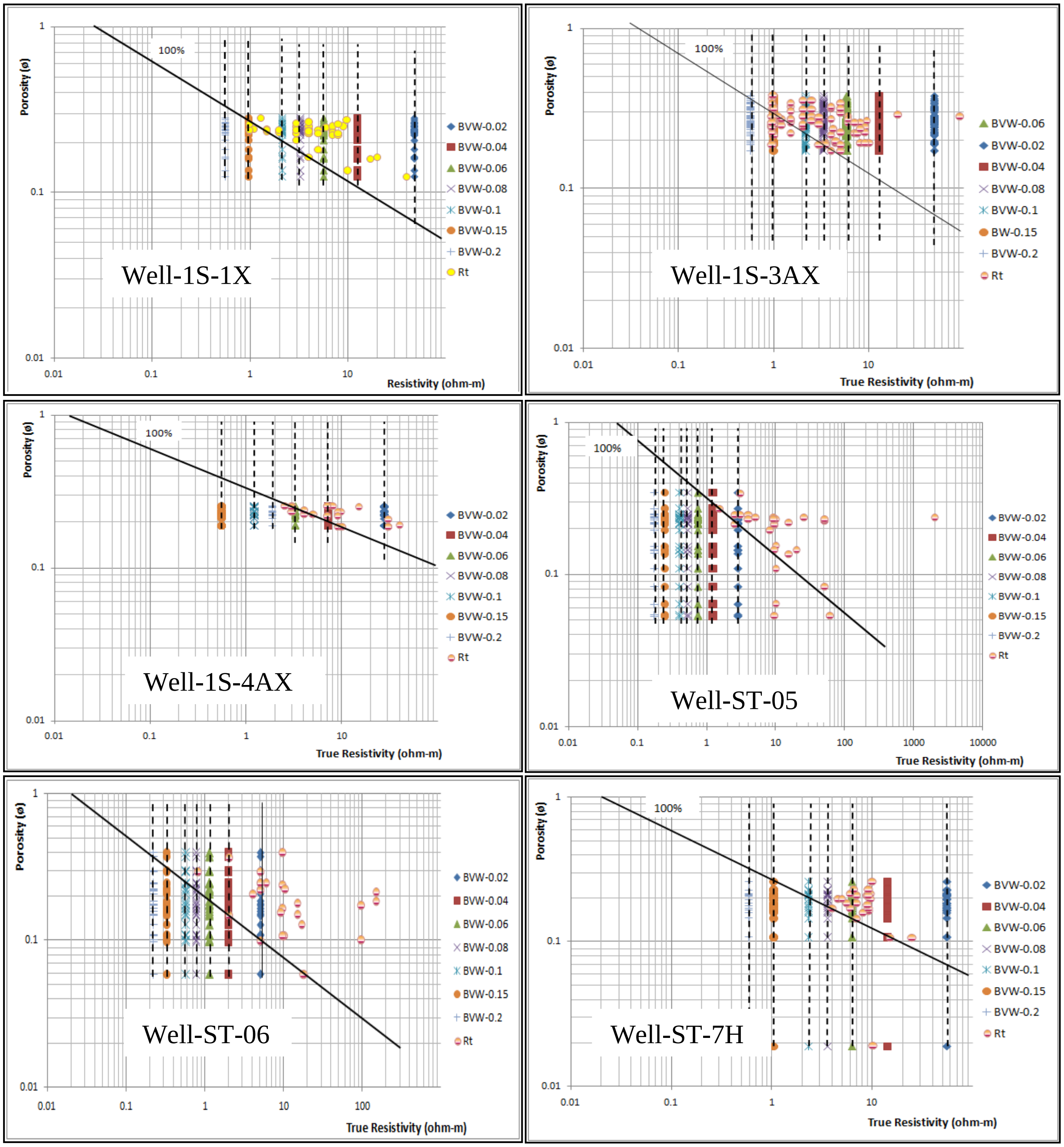


Figure 6. Pickett's plot for the exploratory wells in the western Tano Formation integrated with the bulk volume of water

3.5. Effect of height above the free water surface

Reservoir rock usually contains immiscible fluids which exist in phases: oil, water, and gas. The forces which keep these fluids at equilibrium with each other and the medium is known as capillary forces. The pressure difference existing across the interface separating the fluids is referred to as capillary pressure [14-18]. Accordingly, the height of hydrocarbon column above the free water surface can be expressed as a linear function of the capillary pressure existing between the fluids as

$$h = \frac{P_c}{0.433(\rho_w - \rho_{hc})} \quad (24)$$

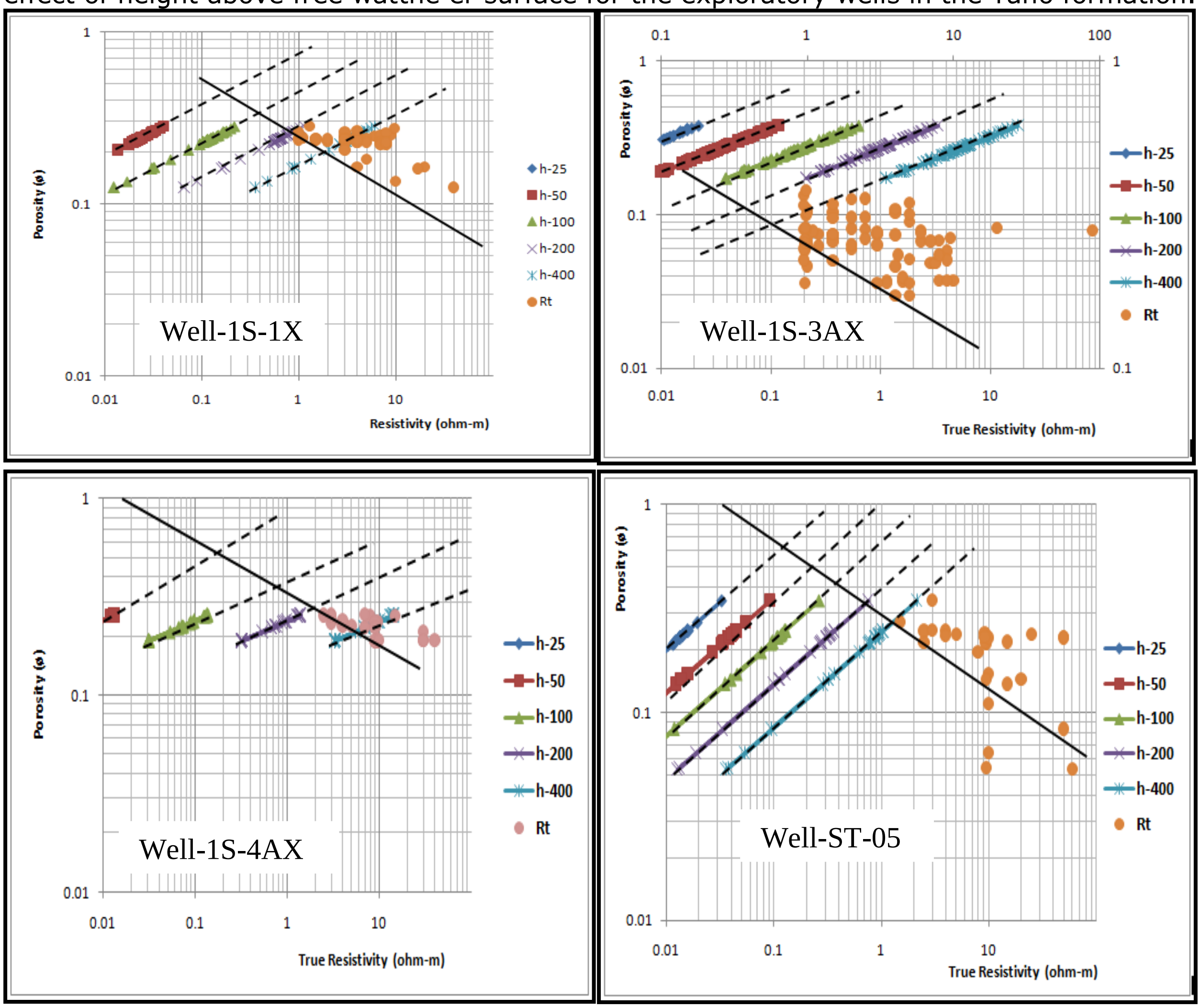
where subscripts *w* and *hc* denote wetting phase and non-wetting phases, respectively, ρw and ρhc are densities of the respective phases, and *h* is height above the free water level.

Rearranging and substituting Eq. 24 into Eq. 19and applying logarithm to both sides leads to the form;

$$R_t = a \times \emptyset^{2.8125n-m} \times R_w \times \left[\left(\frac{0.433 \times h\,(\rho_w - \rho_{hc})}{3.033}\right)^{-1.25}\right]^{-n} \quad (25)$$

$$logR_t = (2.8125n - m) \times log\emptyset + log\left[aR_w \times \left(\left(\frac{0.433 \times h\,(\rho_w - \rho_{hc})}{3.033}\right)^{-1.25}\right)^{-n}\right] \quad (26)$$

Eq. 23 presents a straight line with a slope corresponding to *(2.8125n −m)* with constants aR_w, ρ_w, ρ_{hc}, and height above the free water surface. The intercept of the straight line on the true porosity plot correspond $\left[aR_w \times \left(\left(\frac{0.433 \times h\,(\rho_w - \rho_{hc})}{3.033}\right)^{-1.25}\right)^{-n}\right]$. Figure 7 exhibits the effect of height above free watthe er surface for the exploratory wells in the Tano formation.



Well-ST-7H

Well-ST-06

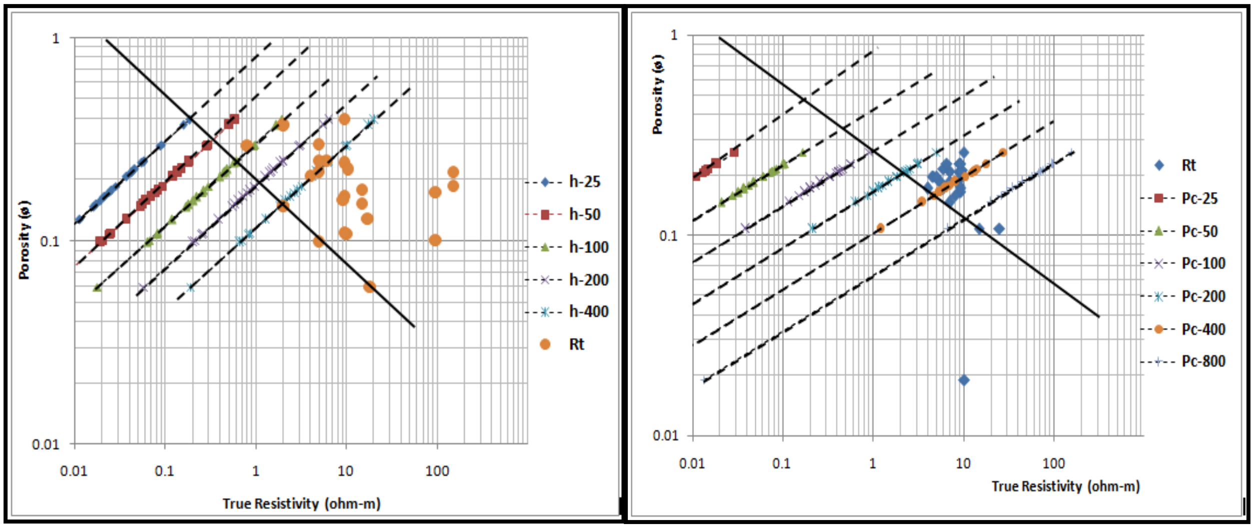


Figure 7. Pickett’s plot for the exploratory wells in the western Tano Formation integrated with height above the free water surface

3.6. The relationship between water saturation and petrophysical parameters

Accurate hydrocarbon reserve in a reservoir formation is very crucial for reservoir economics. One key variable in the determination of the reserve is water saturation amount. Proper evaluation of water saturation leads to adequate reserve estimation. The study compares the relationship of water saturation with Petrophysical parameters such as the bulk volume of water, capillary pressure, and permeability for the exploratory wells used for the study.

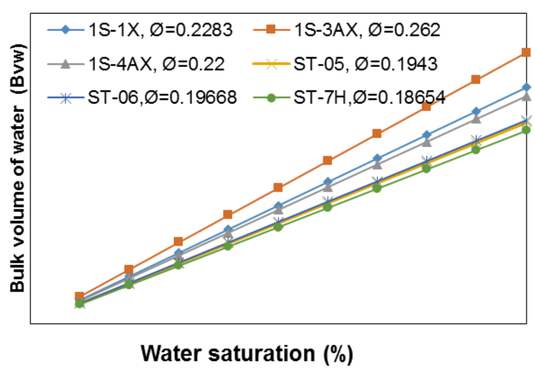


Figure 8. Correlation between the bulk volume of water and water saturation for exploratory wells

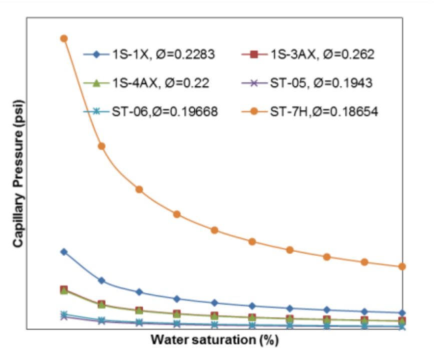


Figure 9. Correlation between capillary pressure and water saturation for exploratory wells

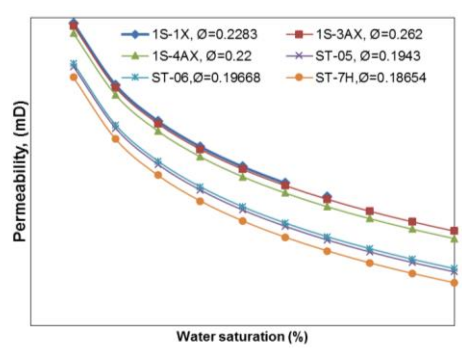


Figure 10. Correlation between permeability and water saturation for exploratory wells

As expected, bulk volume of water is found to be proportional to water saturation and that bulk volume of water increases as water saturation increases, Figure 8. Additionally, as water saturation increases, the pore space within the reservoir gets filled up with water, and this has a reduction effect in both permeability and capillary pressure, Figure 9 and Figure 10.

4. Results and discussions

An approach which integrates the Petrophysical constants of the Tano formation has been established via the Pickett's resistivity and porosity model. The approach incorporates in the Pickett's models such Petrophysical parameters as specific surface per unit pore, permeability, capillary pressure, bulk volume of water and height above the free water surface.

The specific conclusions are as follows:

The study shows different results and effects of the various Petrophysical parameters considered which depend on the log-log plots of resistivity and porosity. For a given resistivity, porosity decreases with increasing permeability, capillary pressure, and height above the free water surface.

Resistivity approximates zero slopes with specific surface per unit volume and bulk volume of water the slope being affected by the porosity of different exploratory wells. There is, however, the marginal increasing effect of specific surface per unit solid volume and bulk volume of water. The slopes of all the plots are affected by the saturation and porosity exponents. These exponents as wells apparent water resistivity for the formation have been determined.

Finally, it is observed that water saturation has an inverse relation with both capillary pressure and permeability but a direct relation with the bulk volume of water.

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