Experimental basis for prediction of cementation, water saturation and bound water volume exponents with grain size variation in fresh water fluvial reservoirs

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Abstract

Determination of hydrocarbon saturation in fresh water fluvial reservoirs has long been a challenge because of the complexities of the electrical conductance mechanism varying in the range from Archie, non-Archie to a severely non-Archie behavior of electrical conduction where conventional shaly sand equations breaks down. Accordingly, Archie, shaly sand and pseudo-Archie methods applied for precise computation of water saturation in these reservoirs. The only practical means at present of obtaining the realistic values of Archie parameters is by using tedious, expensive, and time-consuming core measurements with very high sampling rate. There has been doubts about the validity of the computed constant values from such core measurements, as these measurements do not reproduce down hole conditions particularly in heterogeneous reservoirs with continuous textural variations.

To overcome these limitations, all the published core data sets of Winsauer , Waxman-Smits and fresh water fluvial reservoirs of Upper Assam and Krishna Godavari Basins of India have been analyzed to develop a unified approach to take care of anomalous reduction of formation resistivity factor in all type of facies varying from Archie to severely non-Archie in fluvial reservoirs. Empirical inter relationships evolved through core data have been extended log scale with different in-situ boundary conditions particularly in shaly/silty beds. Concept of Archie bound water exponent, which equates to the cementation and saturation exponents, has been pursued for the integration of in-situ resistivity and nuclear magnetic resonance log measurements with core data in hydrocarbon zone as electrofacies of aquifer zone, generally do not make an exactly similar reference for the prediction of water filled rock resistivity in hydrocarbon zone.

From the empirical relationships derived from core data, the linear correlation of tortuosity, Archie parameters and grain size has been found. Linear increase of excess conductivity with decrease of grain size is noticed on all the low salinity core measurements i.e. linear reduction of formation factor with grain size. Linear decrease of cementation and bound water exponents are noticed on all the low salinity measurements. However, these parameters are showing linear increase with decrease of grain size on high salinity measurements. Any linear relation can be easily converted into a unified volumetric average relationship with boundary conditions with reality checks in clean sands and silty/shale beds. Prediction of formation resistivity factor derived through unified volumetric average relationships are validated with actual core measured values. A generalized least square relationship to account for the surface conductance associated with grain size variation has been evolved through linear regression analysis for precise prediction of Archie parameters from core data, which can be extended to log measurements.

Introduction

Archie (1942) equation, $S_w{}^n = R_o/R_t = FR_w/R_t = a\,R_w/R_t\,\phi^m$ is the basic equation to compute water saturation S_w in clean formation with resistivity R_t . It is a combination of two empirical equations, where first fully water saturated resistivity R_o is derived from the product of formation water resistivity, R_w and formation factor F, related with porosity, ϕ as $F = a/\phi^m$, where the constants *'a'* and porosity exponent '*m'* are related to rock type and determined through regression method. Archie also derived another empirical expression for partially water saturated rocks with fraction S_w, based on its resistivity ratio with fully water saturated rock referred to as the Resistivity Index, $I_r = R_t/R_o = (R_t/R_w)/(R_o/R_w) = G/F = S_w^{-n}$, where the exponent '*n*' was termed as saturation exponent is also derived through regression and G is generalized formation factor in case of partially saturated rock.

Archie's empirical relationships are applicable to a wide range of rock types known as Archie rocks, where electrical conduction is only through brine in pores with non-conducting rock matrix. In such type of fully water saturated rocks, resistivity R_o is directly proportional to R_w i.e. constant of proportionality $F = R_o/R_w$ is independent of salinity. Similarly, constant R_t/R_o is also independent of salinity. Values of m and *n* in Archie rocks were found to be constant i.e. *m= n =2.0*.

In clean sands with saline pore fluid in insulating matrices, accuracy of Archie's equation is well established. Deviation of either of the conditions i.e. conduction of currents through matrix like clay/shale or salinity lower than *20* grams per liter (gpl) or both, rocks exhibit excess conduction in addition to brines in pores and such type of rocks are known as non-Archie rocks. These types of rocks conducts electrical currents according to Archie equation with reduced formation factors i.e. reduced values of *m* and *n* parameters in proportionate to the reduction in salinity. Non Archie effects are further amplified with decrease of salinity of brines, even with nominal or without presence of clays.

Water saturation estimation in fresh water fluvial reservoirs of has long been a challenge because of the complexities of the electrical conductance mechanism varying in the range from Archie, non-Archie to a severely non-Archie behavior of electrical conduction where conventional shaly sand equations breaks down. Quantitative log interpretation using pseudo Archie method take care of all type of reservoirs but the accuracy of water saturation value for given reservoir conditions depends on the accuracy of Archie parameters *a*, *m* and *n*. The only practical means at present of obtaining values of Archie parameters is by using tedious, expensive, and time-consuming core measurements with very high sampling rate. There has been doubts about the validity of the computed constant values from such core measurements, as these measurements do not reproduce down hole conditions particularly in heterogeneous reservoirs (Yadav et al, 2017). This has necessitated the development of empirical interrelationship of Archie parameters with grain size, which can be used for prediction of these parameters in down hole conditions viz. any grain size indicator log for precise estimation of water saturation.

In this paper, all the published core data sets of Winsauer, et al, 1952, Waxman-Smits, 1968, fresh water fluvial reservoirs of Upper Assam (Yadav, 2015) and Krishna Godavari (Yadav, et al, 2017) Basins of India have been analyzed to develop an unified approach to take care of anomalous reduction of formation resistivity factor in all type of facies varying from Archie, shaly sands to severely non-Archie in these reservoirs. Empirical inter relationships evolved through core data have been extended log scale with different in-situ boundary conditions particularly in shale beds. Concept of Archie bound water exponent, which equates to the cementation and saturation exponents, has been pursued for the integration of in-situ resistivity and nuclear magnetic resonance log measurements with core data in hydrocarbon zone as electrofacies of aquifer zone, generally do not make a proper reference for estimation of water filled rocks resistivity in hydrocarbon zone (Yadav, et al, 2017). Moreover, problem of large scatter or poor correlation of saturation exponents with facies variation, due to its nonlinear dependence with water saturation, can be overcome by using Archie bound water exponent.

Spatial variable nature of porosity, saturation and bound water exponents

Based on a very small data set assembled from around the world, Winsauer et al, 1952, proposed generalized Archie relationship as $F = 0.62\ \phi^{-2.15}$, which is famously known as the "Humble" formula. Winsauer's data with values of *m* was varying in the range of 1.56 – 2.05 mainly due to variations in clay volume in range of 0-9%. Although space variability in *m* was there due to the variation of clay as most natural cause of tortuosity, a force fit with constant *m* and *'a'* was applied by ignoring the space variable nature of *m* as indicated in Fig-1.

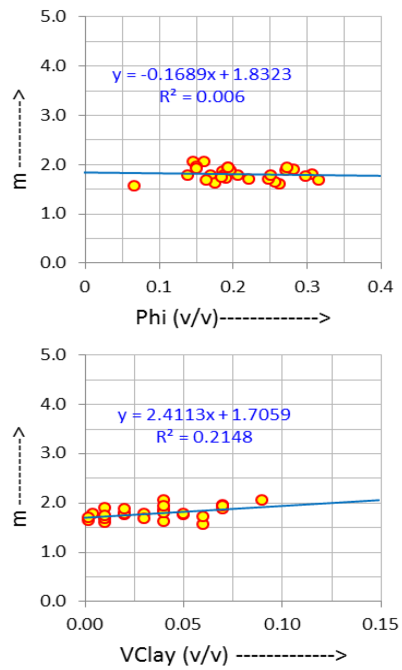

Fig-1. Correlation of m with porosity and Vclay in Winsauer data

Clay volumes are indicating better correlation with *m* as compared to porosity. Regression approach using different electrofacies for derivation of *'m'* as well as *'n'* is still in practice/ continuing, which nullifies the effect of spatial variability of the parameter and is main source errors in the Petrophysical evaluation of fluvial reservoirs.

Apparent formation factors and resistivity index exhibit very large variations related with variations of *m* and *n* in fluvial reservoirs and a variable *'m'* approach has to be pursued by assuming *a=1* and calculating *m* from the definition $m = -logF/log\phi$, where *F* and ϕ are obtained from single measurement and the derived parameter *m* is now spatially variable.

In the case of low resistivity fluvial reservoir rocks, plotting of I_r versus S_w can produce a variety of nonlinearities in a *log* I_r versus *log* S_w plot that are impossible to interpret in terms of the simple Archie equation as indicated in Fig-2. Plots are showing variations of *n* beyond the limits of measurement uncertainty that does not conform to the Archie supposition of constancy. Assumption of constancy of *n* are not always justified in such cases, a variable '*n'* approach is pursued by calculating *n* from the definition $n = -logI_r /log\ S_w$, where I_r and S_w are obtained from single-desaturation measurements and *n* is spatially variable. It is erroneous to derive an average value of *n* by averaging different electrofacies with *n* varying in very large range with more than *100%* deviations.

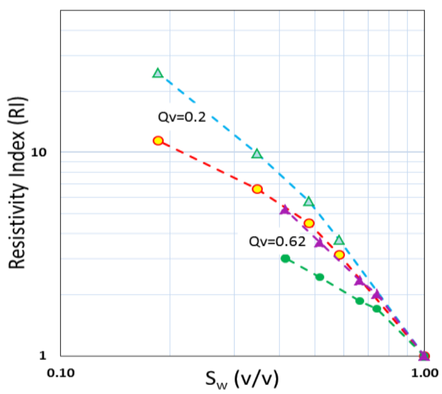

Fig-2. Nonlinearity of n with S_w at low and high salinity core measurements in non-Archie fluvial reservoirs

Recalling that Archie's equation is assembled from $F = R_0/R_w = a\phi^{-m}$ and $I_r = R_t /R_0 = S_w^{-n}$ by elimination of R_0, forming the product I_rF, a plot of $I_r\ F\ (=G= R_t /R_w)$ against $\phi\ S_w$ is a graphical means of achieving a similar result, where Archie bound water exponent is defined as *mn = m=n.* Description of conductivity as power of bulk volume of brine is similar to the combining of first and second Archie laws. Variable *mn* approach is pursued by calculating *mn* from the definition $'mn' = -logG /log\phi S_w$. All resistivity data for the formation resistivity factor plot and resistivity index plot can be represented on this single plot

Prediction of Archie parameters from excess conductivity and its limitations

*F/F** and G/G* ratios can be treated as measure of deviation from Archie's conditions or excess electrical conductance other than water volume and are defined as reduction in the values of *m* and n with respect to their intrinsic values (Worthington, 2006).

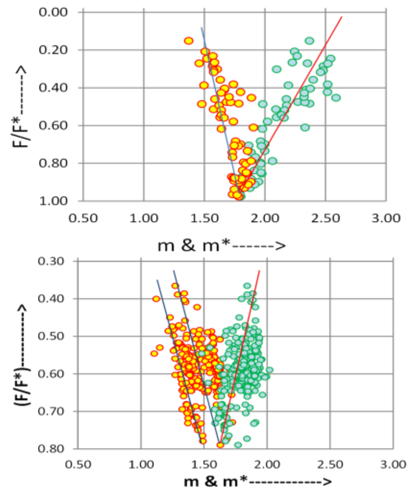

Fig-3. Variation of excess conductivity with m and m for Waxman and Assam data sets*

Based on these ratios he presented classifications of fresh water rocks and suggested that if *m** is known or can be reasonably estimated, it is possible to use $F/F^* = \phi^{m^* - m}$ to make an estimate of *m. Again, if a value can be assigned to n*, it is possible to use* $G/G^* = \phi^{m^* - m} S_w^{n^* - n}$ *to make an estimate of n, and vice versa.*

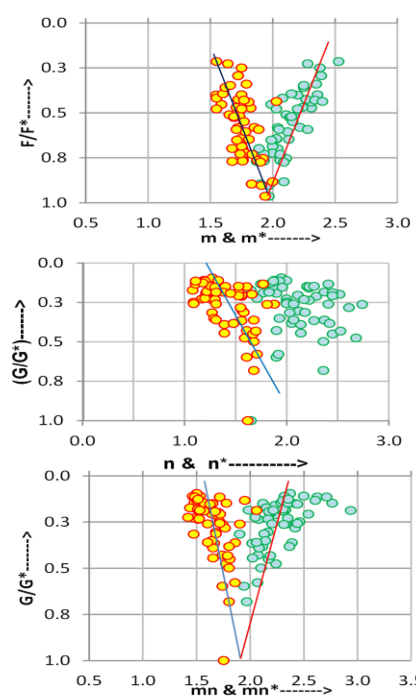

Fig-4. Variation of excess conductivity with apparent and intrinsic Archie's parameters for KG basin data

Application of pseudo Archie method based on prediction of differential *m*-m* and *n*-n* , proposed by Worthington, 2006, for the evaluation of low resistive fluvial reservoirs is quite cumbersome to classify, compute and apply the varying values of '*m*' and '*n*' for the quality assured evaluation of hydrocarbon of reservoirs with continuous textural variations. To overcome these limitations, reduction in formation factor ratio i.e. *F/F** or *G/G** are directly correlated with *m* and *n* for their respective prediction, which are in turn related with grain size as indicated in Fig-3 &4. Yellow and green symbols represent apparent and intrinsic values respectively.

Variation of Archie parameters with tortuosity

The concept of electrical tortuosity can be used to understand conductivity models such as Archie's equation.

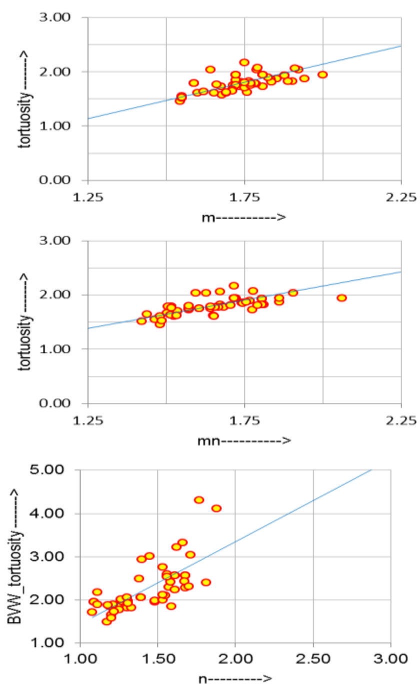

Fig-5. Linear relationships of apparent tortuosity with Archie parameters

Electrical tortuosity τ_o of a water saturated rock is related to the formation factor and porosity as $\tau_o^2=F\phi$. Electrical tortuosity τ_t of a partially water saturated rock is related to the generalized formation factor and bound water volume *BVW* as $\tau_t^{2} = GBVW = G\phi Sw$. Like the cementation exponent, the bound water exponent *mn* describes the change in electrical tortuosity with changes in bound water content. The saturation exponent describes the change in electrical tortuosity with changes in water saturation (Fig-5).

Archie parameters are showing linear relation with tortuosity in fluvial reservoirs as indicated in Fig-3.

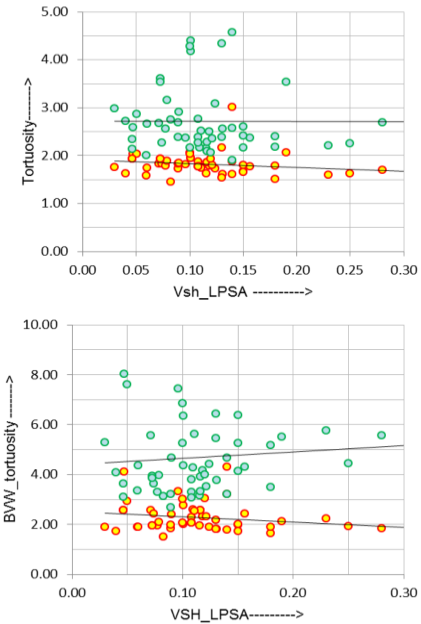

Fig-6. Linear relationships of apparent (yellow) and intrinsic (green) tortuosity with shaliness

Decreasing of *n* and *mn* are resulting in decrease of generalized formation resistivity factors in partially saturated rock similarly as in case of decrease of values of *m* in fully water saturated reservoirs. Apparent torturosity values in fully as well as partially saturated conditions are showing goog linear correlation with LPSA derived shaliness (Fig-6).

Core derived relationship of Archie parameters with grain shaliness

Regression analysis of core data indicates linear relationships of all the Archie parameters with LPSA derived shaliness are shown in Fig-7 and 8 respectively for Waxman-Smits and K G Basin data sets.

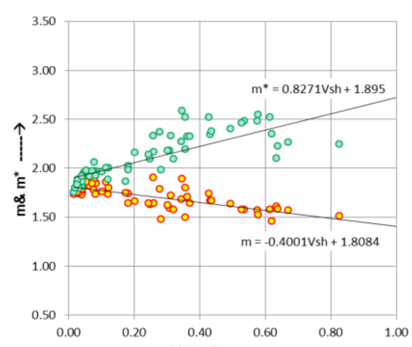

Fig-7. Waxman-Smits data sets showing Linear Relationships of apparent (yellow) and intrinsic (green) values of m with shaliness

In case shaly sands with *Vsand + Vsh =1.0*, any linear relationship either shale volume or sand volume can be converted into a unified volumetric average relationships. Linear relationships of Archie parameters with grain size/shaliness can be converted into following unified volumetric average equation.

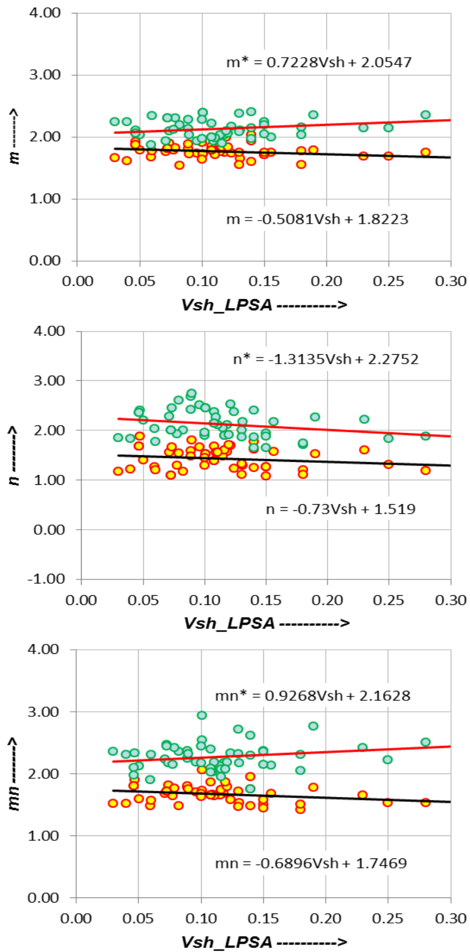

Fig-8. KG Basin data sets showing Linear Relationships of apparent (yellow) and intrinsic (green) values of Archie's parameters with shaliness

Regression analysis of Core derived '*m*', in case of fully water saturated conditions, with *Vshale* LPSA core measurements indicates a linear relationship as

m = 1.8223 – 0.5081 Vsh

Unified volumetric relationship for prediction of composite *m* can defined as volumetric average of end facie values derived from boundary conditions as

*'m' = m_sand * Vsand + m_shale * Vshale*

Where, *m_sand = 1.8223 m_shale = 1.3142*

Presence of hydrocarbon will increase the degree of surface conductance effect upon the measured formation conductivity under partial saturation conditions and will have profound bearing on saturation and bound water exponents i.e. decreased values of *n* and *mn*.

n = 1.519 – 0.73Vsh

mn = 1.7469 – 0.6896 Vsh

Validation of formation resistivity factors derived using Archie parameters predicted by volumetric average relationships

Values of Archie parameters predicted from volumetric average relationships have been used for estimation of formation resistivity factor in fully water saturated conditions and generalized formation resistivity factors in partially saturated reservoirs.

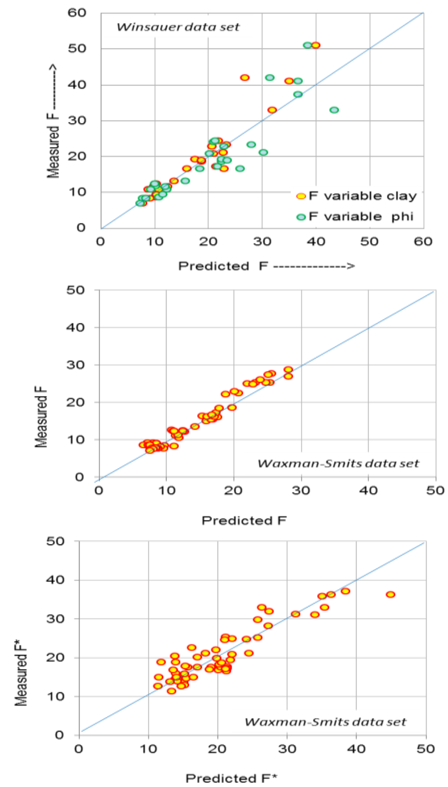

Fig-9. Validation of Winsauer and Waxman-Smits data with predicted values of m using volumetric average relationship of shaliness

These values have been validated with respective actual measured values Validation of Winsauer data set using *Vclay* is presented in Fig-9. Values of formation factors derived from variable porosity concept (Sethi, 1979) has also been presented with green color circles for the comparison purpose. Values derived from two different approaches are showing similar scatter around 45^0 line between estimated and measured values of formation factors. Apparent and intrinsic value of formation factors have been predicted for Waxman-Smits data set is showing excellent correlation with measured values.

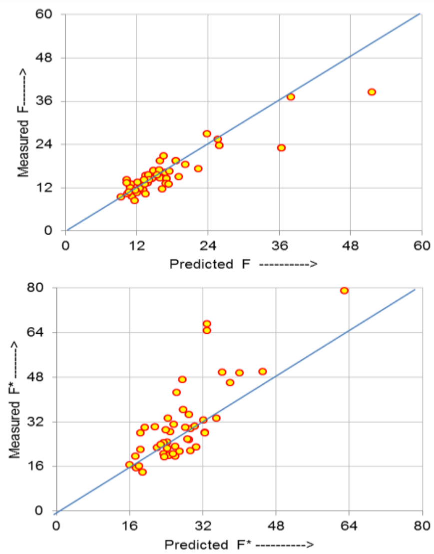

Fig-10. Validation of KG Basin data with predicted values of m using volumetric average relationship of shaliness

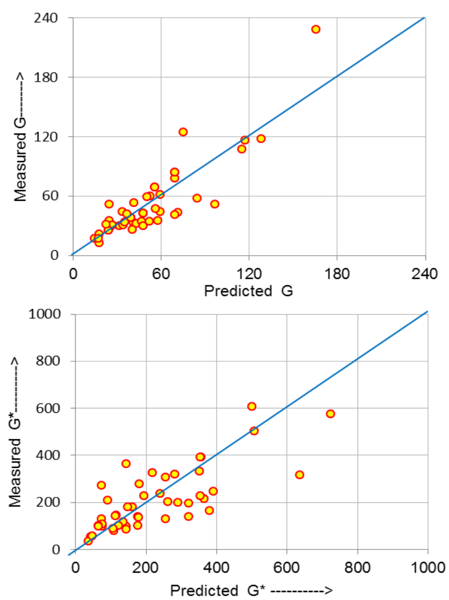

Fig-11. Validation of KG Basin data with predicted values of mn using volumetric average relationship of shaliness

Apparent and intrinsic values of formation factors in fully and partially water saturated reservoirs derived from volumetric average relationships are respectively presented in Figs- 10 and 11 for the data sets of KG basin.

Apparent values used for pseudo Archie method are showing better correlations as compared to the intrinsic values which generally used in shaly sand equations.

Discussion and conclusions

Problem of low resistivity in fluvial reservoirs was well recognized with reduction in formation factor at lower salinity on electrical core measurements. Many investigators have noted that the apparent formation factor of porous materials will diminish as the interstitial water becomes more fresh (Winsauer and McCardell, 1953, Hill and Milburn, 1956, Turcan, 1962, Evers and Iyer, 1975).

This effect has been attributed both to conductive solids shale/clay and to the existence of a concentrated layer of ions adsorbed on the surface of the rock matrix. The first results, obtained from the oil industry during the study of brine-saturated formations (Archie, 1942, Tixier, 1958, Carothers, 1968) showed that formation factor increases as porosity and permeability decrease. On the other hand similar investigations concerning fresh-water aquifers (Alger, 1966, Croft, 1971, Kosinski and Kelly, 1981) showed that the formation factor increased with permeability at constant porosity, while some other researchers (Barker and Worthington, 1973, Worthington, 1977, Heigold et al., 1979) found an inverse relationship between formation factor and permeability.

In case fresh water evaluation (Fresh water Industry), it is well established that formation factor, tortuosity, *m* and permeability vary proportionally with grain size (Evers and Iyer, 1975). The relationship between permeability, formation factor and grain size is very important in evaluating water wells from log data but it is the reverse of that commonly accepted in oil industry. Because the importance of surface conductance increases with decreased water salinity, the concept must be changed for sands containing fresh water. Sarma and Rao, 1963, have reported the variation of formation resistivity factor with formation water resistivity for medium to coarse grain sizes of quartz powder. Variation of formation factor is more with the decrease of grain size and increase of formation water resistivity.

All the data presented indicate the linear correlation of tortuosity with formation factor, Archie parameters and grain size. Different data sets belonging to different depositional setups are easily differentiated in Waxman-Smits and Upper Assam data sets, particularly on respective intrinsic values. Linear increase of excess conductivity with decrease of grain size is noticed on all the low salinity core measurements i.e. linear reduction of formation factor ratio with grain size. Linear decrease of cementation and bound water exponents are noticed on all the low salinity measurements. However, these parameters are showing linear increase with decrease of grain size on high salinity measurements. Any linear relation can be easily converted into a unified volumetric average relationship with boundary conditions with reality checks in clean sands and silty/shale beds. Prediction of formation resistivity factor derived through volumetric average relationships have been validated with actual core measured values. A generalized least square relationship to account for the surface conductance associated with grain size has been evolved through linear regression analysis for precise prediction of Archie parameters from core data, which can be extended to log measurements viz. resistivity and nuclear magnetic resonance logs in the reservoirs. Petrophysical evaluation of open hole logs performed with variable *m* approach, have resulted in a realistic evaluation of low resistive fluvial formations corroborating with the available core measurements and testing results (Yadav, 2015, Yadav, et al, 2017).

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