Anomalous relationship of conductivity with water salinity and saturation in fresh water fluvial reservoirs of Krishna Godavari Basin, India

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Abstract

Clay free, Archie reservoir rock conductivity increases linearly with brine conductivity from the origin. Shaly sands/clay-bearing rock also responds linearly like clean sand, but only at elevated conductivity values. The amount of displacement above the clay free line is related to the excess conductivity, BQ_v due to the presence of conductive clay minerals. B introduced by Waxman-Smits represents the equivalent conductance of the counterions as a function of brine solution conductivity and Q_v representing volume concentration of clay exchange cations. Most practical applications of this model equation is based on establishing a linear trend, in high salinity region, on a plot of rock and brine conductivity data derived from core measurements in the laboratory. Where salinities are relatively high equation adequately reduce the uncertainty in hydrocarbon saturation estimates in variety of shaly sand reservoirs.

Under decreasing electrolyte concentration, clay excess conductivity shift becomes non-linear towards the origin because clays conductivity predominates in the relative absence of free ions in the increasingly fresh formation water. In the nonlinear region, Waxman-Smits model has met with limited success particularly in fresh water fluvial reservoirs. Anomalous conductivity relationships with water salinity and saturation in partially as well as fully water saturated conditions have been found in these reservoirs. This was mainly due to empirical model assumption of exponential increase of equivalent conductance of clay exchange cations (sodium) mobility, B with increase in solution conductivity from an initial value of *18.4*, when solution conductivity is zero, has been derived by apparent agreement with the reported conductivity measurements of sodium montmorillonite-distilled water gel.

In this paper, based on extensive set of laboratory electrical core measurements, a reliable interpretation model has been found by adjusting the standard Waxman-Smits model with only different equation for the B factor as function of solution water salinity. Results are presented with multiple salinity electrical measurements of a large number of core samples from two wells penetrating the fresh water fluvial sandstone formations of Krishna Godavari Basin, East Coast, India. A comparison of electrical conductivity data with Waxman and Smits shaly sand samples measurements clearly indicates that samples from fluvial reservoir rock are showing anomalous deviations from high salinity trend line and does not conduct through Waxman-Smits shaly sand mechanism in low salinity region even with similar values of volume concentration of clay exchange cations, Q_v.

Extrapolations were made on multiple salinity conductivity measurements of each plug using least squares fit to estimate surface conductivity, BQ_v. Derived values of BQ_v were plotted against the independently measured values of Qv for the plugs in each well to estimate respective average value of B as 48.532 and 39.4569. The data were fitted by a straight line passing through origin in least square regression with very high correlation coefficient values of 0.96 and 0.99 respectively arrived in these wells. Limiting values of B, when solution conductivity is zero, were derived as 20.5 and 17.9 using average values in Waxman-Smits empirical equation. Conductivity data have been showing large deviations from linearity in low salinity region with use of these parameters in Waxman-Smits equations.

To overcome the limitations of misfit of conductivity data in low salinity, process of estimation of average value of B was repeated with actual surface conductivity calculated as difference between rock conductivity and solution conductivity. Low salinity conductivity data have been found to be showing excellent fit with correlation coefficient in range of 80-94. New average B values of 24.855 and 23.387 have been derived from actual surface conductivity. New minimum limiting value of B is estimated to be close to 10 in both wells. Waxman-Smits equations with following modified B as function of solution conductivity have been proposed respectively in these wells, which show excellent fit of conductivity data in low as well as high salinity regions.

$B=[1-0.79\ \mathrm{Exp}\ (-0.013C_w)]48.5$ I
$B=[1-0.75\ \mathrm{Exp}(-0.025\ C_w)]39.459$ II

Predicted values from these equations adequately compensate for surface conductivity and excess conductivity derived from formation factor ratios in fully as well as partially saturated conditions. Conductivity values derived from these equations have been validated with respective core measured values with excellent agreement. New approach can be extended to any fluvial reservoirs to evolve field specific water saturation equation with modified Waxman-Smits model.

Introduction

Archie (1942) equation, $C_o = C_w/F$ is sufficient to describe overall rock conductivity, C_o where the rock is free of clay minerals and where solution conductivity, C_w is sufficiently large to suppress any other mineralogical influence on current flow, e.g. a surface charge on quartzitic silt, its accuracy is well established. This relation assumes conduction through the fluid phase only; the electrical conductivity of the rock solids is considered to be negligible so that a bilinear plot of C_o vs C_w furnishes a straight line through the origin of gradient $1/F$, where formation factor, F is an intrinsic rock property that remains constant with varying fluid conductivity. Change on either of the condition i.e. conduction through matrix due to presence of clays or low brine salinity or both results in a change of formation factor with formation water salinity i.e. F varies with Cw and become apparent quantity.

In shaly sands, the presence of clay adds an additional conductivity causing an error in water saturation estimation. The original Archie's Law was modified by Waxman and Smits,WS in 1968 to account for the effect of chemically active clays. WS shaly sand model consists of two resistance elements in parallel, one component consisting of the free electrolytes in pore volume of the rock, C_w and another resulting from the conductance contribution of the exchange cations associated with the surface conductivity of clay C_c. Electrical current transported by counter ions associated with clay travels along the same path as the current attributed to the ions in the pore water, $C_o = (C_w + C_c)/F^*$. On a C_w–C_o plot as indicated in Fig-1, C_s(or C_c)represents a negative value of C_w when C_o is equal to zero. Surface conductivity term has been denoted as C_s in context of fluvial reservoirs, where surface conductivity may or may not be due to clays. Shaly sand reservoirs exhibit additional conductivity C_r at origin i.e. presence of rock conductivity due to presence of shale even if brine conductivity, C_w is zero i.e.

$$C_o = C_w/F^* + C_r$$

At higher salinity, change in C_c will tend to zero and core samples will exhibit scatter according to the variation of F^* which is directly proportional to the shale volume.

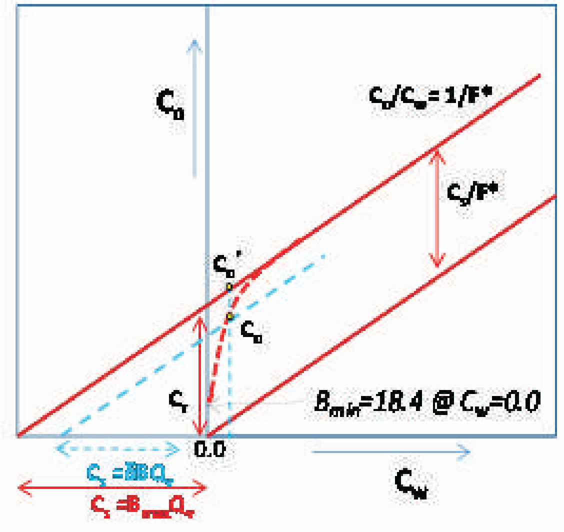

Fig. 1: Rock conductivity, Co as function of Solution conductivity Cw (Waxman-Smits -1968)

The problem in dealing with electrical response of shaly sand is to quantify C_r or $C_c = F^* C_r$, the shale's electrical conductivity. On a C_w–C_o plot, C_c represents a negative value of C_w when C_o is equal to zero. It becomes constant in the higher salinity range where change due to clay effect is negligible and conductivity becomes a linear function of C_w. Clay-bearing rock also responds linearly, but only at elevated C_o values. The amount of displacement above the clay free line is related to the excess conductivity (BQ_v) due to the presence of conductive clay minerals. B was introduced to represent the equivalent conductance of the counterions as a function of brine solution conductivity and Qv representing concentration of sodium exchange cations associated with clay.

WS model has become the most fully developed and widely accepted approach to the understanding of electrical conductivity of shaly sand formations. Most practical applications of the WS or Dual Water Model (Clavier et al, 1977) equations are based on establishing a linear, high salinity region on a plot of C_o versus C_w data derived from core measurements in the laboratory. Where salinities are relatively high conventional shaly sand equations adequately reduce uncertainty in hydrocarbon saturation estimates. However, at low salinities, and in the presence of clay minerals, C_o is insensitive to C_w and the excess conductivity term will predominate in all commonly used shaly sand equations.

Clay excess conductivity shift becomes non-linear toward the origin because the excess conductivity associated with the clays predominates in the relative absence of free ions in the increasingly fresh formation water. Empirical techniques have been developed for the non-linear region (Sen, et al, 1988) but the solution always becomes more uncertain towards the origin. Under decreasing electrolyte concentration, the effective formation factor decreases as surface conduction short circuits the pore-water conduction pathways. Shaly sand equations break down when surface conductivity exceeds brine conductivity (Worthington, 2006).

Electrically, the low resistivity problem is not just a *CEC* problem; in fact, surface conduction is just one expression of the problem. Most of the low resistivity sandstones have contained very small amounts of high *CEC* minerals, if any at all (Givens and Schmidt, 1988). Clay free, Archie reservoir rock conductivity increases linearly with brine conductivity from the origin at a slope ($C_o/C_w = 1/F = 1/F^*$) related to the rock fabric, where F^* denotes the intrinsic or clay corrected formation factor. At low salinity rock conducts with reduced apparent formation factor F ($= C_w/C_o$) and Waxman-Smits equation becomes,

$$C_w/F = (C_w + BQ_v)/F^* \text{ or } F^*/F = (C_w + BQ_v)/C_w$$

Formation factor ratio or reduction in apparent formation factor with respect to its intrinsic or clay corrected value is a measure of excess conductivity in shaly sand rocks. It defines the new origin as if rock is saturated with water having apparently more conductivity of ($C_c + C_w$) instead of C_w as predicted from brine salinity. The ratio F^*/F is unity in the absence of lithology effects and greater if significant effects are present. This equation shows that F^*/F is equal to the ratio of total conductivity to the 'clean' conductivity. It is quite feasible to have alithologically clean sand that shows extreme shale effects, i.e. is a non-Archie formation, solely because of low electrolyte salinity. On the other hand, a lithologically shaly sand might show no shale effects, i.e. be classified as an Archie reservoir, where electrolyte salinity is very high (Worthington, 1991).

This pore fluid effect is more pronounced at lower salinity resulting in an anomalous reduction of formation factor in partially water saturated state. The excess conductivity BQ_v is amplified in partially saturated conditions i.e. BQ_v becomes BQ_v/S_w. If water saturation is in the range of 0.5 to 0.2, excess conductivity term is amplified by 2 to 5 times as compared to the fully water saturated conditions. A rock can behave as an Archie or non-Archie shaly sand rock in the fully water-saturated state and yet show non-Archie or severelynon-Archie characteristics respectively in partially water-saturatedstate where shaly sand equations break down. Fresh water fluvial reservoirs generally exhibit a shift in the nature of shaly sand reservoir in fully water saturated condition to a severely non Archie nature in partially saturated condition. Application of a particular equation to estimate water saturation is also governed by the nature of their pore fluids.

From the petrophysical standpoint, W-S needs three types of special core analyses: CEC from electrochemistry, C_o-$C_w$to define m^*, and resistivity index vs Sw measurements at different C_w's to obtain an average n^*. The product of Q_v, concentration of sodium exchange cations associated with the clay, and B symbolizes conductivity of clay depends on electrochemistry, assuming that the exponential correlation of B is universal. The equivalent cation conductance B is forced to fit a non-linear response at low water salinities, without any theoretical justification. Moreover, definition of the B function implies a similar curved shape in the C_o-$C_w$plot at low values of C_w, irrespective of shaliness or clay type. Re-analysis of W-S experiments, completed by Brown (1988), shows that it is not true and that B should be shale dependent (Clavier, et al, 1984).

For better understanding, WS equation is rewritten in its general form as $C_o = (1 + X)C_w/F^*$, where X is the dimension less excess conductivity associated with the clay counterions and is a characteristic variable used directly or otherwise included in most shaly sand conductivity models (Worthington, 1985). In the WS model, $X = BQ_v/C_w$, and becomes a simple additive excess. Grain conductivity models (Bussian 1983; Lima and Sharma,1990) use this ratio in power laws involving the cementation exponent. Realistic values of X at low values of salinity vary from 2-10 depending on Q_v. At very high values of salinity this ratio approaches zero. Values of X can be calculated as a function of BQ_v/C_w, where B at 25 deg C is evaluated from an empirical fit given by Waxman and Smits (1968) to be

$$B = [1 - 0.6\exp(-C_w / 0.013)]0.046$$

While B represents the well understood electro chemical phenomena of ionic mobility, it is the one free parameter that is used in the empirical Waxman-Smits regression in low salinity region. Regardless of the phenomenological accuracy of B, it is worthwhile recognizing that the product BQ_v represents the experimental excess conductivity due to the clay exchange cations at various values of salinity and can be used in calibrating any proposed conductivity model.

In this paper, extensive set of laboratory electrical core measurements of formation factor and resistivity index at multi-salinity @ *6.5, 8, 13.8, 100* and *200 kppm* of *NaCl* on fifty core plugs from two conventionally cored wells, covering entire range of facie of heterogeneous reservoirs of fresh water fluvial sandstone formation of Krishna Godavari Basin, East Coast, India has been presented for detailed characterization of anomalous deviations of excess conductivity from WS model particularly in low salinity region. A reliable interpretation model has been found by adjusting the standard Waxman-Smits model with only different equation for the B factor as function of solution water salinity, which takes care of anomalous deviations in nonlinear low salinity measurements in fully as well as partially water saturated core samples.

Formation factor and resistivity index measurements

The *200 kppm* brine was flowed through each sample. Electrical resistivities (conductivities) of both the saturated samples (C_o) and the saturant brine (C_w) were monitored on consecutive days until they were stable, indicating ionic equilibrium in the porespaces. Two additional brines, in decreasing salinity (*100 kppm* followed by *8 kppm*) were then flowed through each sample. For each salinity at least *10* pore volumes throughput was used (at a slow rate of *0.5mL/min*) before measurement of C_o. These C_o measurements were repeated on successive days until stable – several days were often required at eachbrine salinity for ionic equilibrium to occur. From the data acquired, formation resistivity factor values were calculated. C_o vs C_w values were plotted for each sample and a line regressed through the data points to enable calculation of F^* from the reciprocal of slope of the line and BQ_v from the intercept of the line i.e. equal to the value of C_w when C_o is zero.

The 100% brine saturated samples were desaturated at incrementally increasing capillary pressures using humidified air as the displacement medium. Ceramic porous plates were used for desaturation. The porous plates were saturated along with the samples (100% S_w) prior to loading. Effluent water volumes were monitored by pipette for each sample until stable partial S_w values were achieved at each pressure increment. The resistivity of each sample was thenre-measured and resistivity index, I_r values calculated for derivation of saturation exponent n values.

The trim-ends of selected routine core analysis plugs were cleaned in toluene and methanol, dried at 95°C in a non-humidified oven and then subjected to determinations of cation exchange capacity (*CEC*) using the ammonium acetate wet chemistry technique. These *CEC* values are used to calculate intrinsic m^* and n^* values using Waxman-Smits-Thomas equation.

All the parameters like m, n, m^*, n^*, BQv, G and G^* are derived from F and I_r measurements using Archie and Waxman–Smits equations. Extrapolations were made on multiple salinity conductivity measurements of each plug using least squares fit to estimate surface conductivity, BQ_v.

$$G = R_t/R_w = C_w/C_t = (R_t/R_o)(R_o/R_w) = I_r\, F$$

Deviations of conductivity data with Waxman-Smits model on low salinitymeasurements

Waxman and Smits, demonstrated that the cation exchange capacity per unit volume, Q_v is itself related to shale conductivity as $C_c = BQ_v$ and rock conductivity, $C_o=(C_w+BQ_v)/F^*$, where B is empirical factor for the conductance of clay per exchangeable cation. It is an exponential function of C_w which increases with salinity or C_w.

$$B = \{1 - 0.6\exp(-0.77C_w\}\, B_{max}$$

Values of F^* and B_{max} have been derived from slopes and intercepts respectively of the straight line portions of the C_o-C_w plots of each plug as indicated in Fig-1.Waxman-Smits derived this empirical equation using very low salinity sample measurements of shaly sands of Group-II with $B_{max}=46$ $mho\ cm^2 equiv^{-1}$. This equation is resulting in a calculated value of $B_{min}=18.4$, when $C_w = 0.0$ *i.e.* equivalent ionic conductance of the sodium exchange cations associated with clay was justified by apparent agreement with the laboratory measured value of *18.0* reported by Van Olphen and Waxman(1958) for conductivity measurements of sodium montmorillonite-distilled water gel. This was probably due to presence of similar type clays with high *CEC*in both of the experiments. *CEC* associated with shaliness dominates towards lower salinity but at higher salinity shale component becomes inert as compared to $C_w$and produce linear trend similar to clean sand. At low salinities, non-linear shift toward the origin becomes relatively more sensitive according to the other type of source of surface conductivity like quartzitic silt in presence or absence of other type of clay minerals in fresh water fluvial reservoirs restricts the universal applicability the equation.

To see the agreement between of conductivity measurements at different solution or brine conductivity, four samples of Waxman-Smits with similar $Q_v$values have been presented in Fig-2.This indicates that samples from fluvial reservoir rock are showing large deviation from high salinity linear trend line $(C_o'–C_o)$ and does not conduct through Waxman-Smits shaly sand mechanismin low salinity region even with similar values of volume concentration of clay exchange cations, Q_v. Conductivity deviations in low sanity range are not visible on shaly sand plug measurements presented by Waxman-Smits.

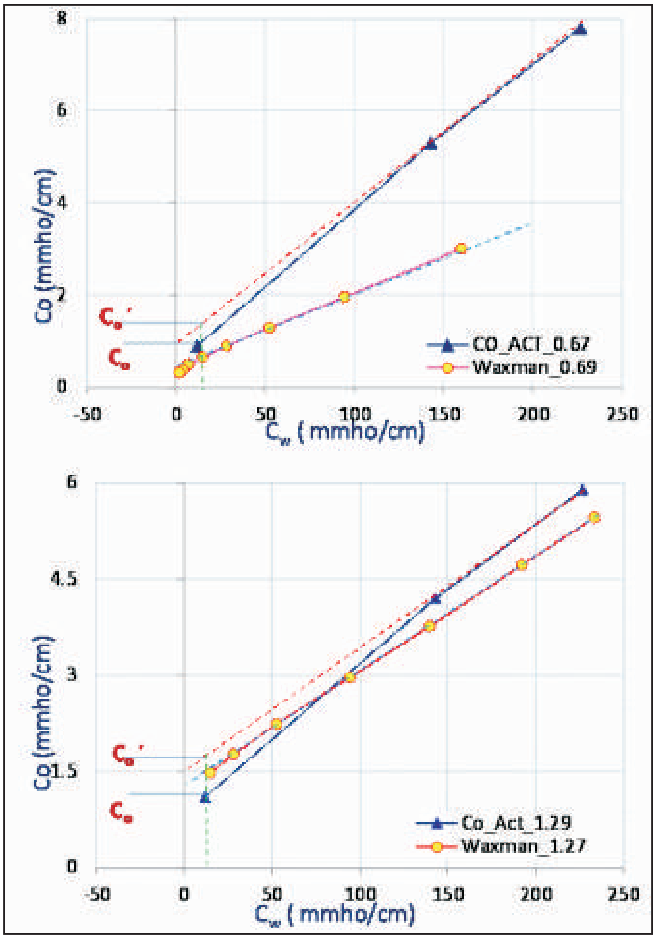

Fig. 2: Comparison of conductivity curves between Waxman-Smits and fresh water fluvialrock samples with similar Qv values

Surface conductance phenomenon associated with fine quartzitic fines/silts in absence or nominal presence of clay minerals, in most of the low resistivity fresh water fluvial sandstones exhibit anomalous deviations from Waxman-Smits equation particularly in nonlinear region.

Derivation of upper and lower bound of *B* for low and high salinity measurements

Extrapolations were made as indicated in Fig-1 using least squares fit to calculate BQ_v values for each plug multiple salinity measurements. Derived values of BQ_v of each plug were plotted against the independently determined values of Q_v for the plugs in each well as indicated in Figs-3, 4 and 5,respectively for high and low salinity measurements as indicated. Average B_{max} values of *48.532, 39.459* and *40.214mho* $cm^2 equiv^{-1}$have been derived from linear trend.

The data sets were fitted by a straight line passing through origin in least square regression approach and very high correlation coefficient values of *0.99, 0.96* and *0.97* respectively arrived in these wells. B_{min} values in the range of *17.9 -20.5*, are consistent with Waxman-Smits after applying the boundary conditions of $C_w=0.0$ on the empirical equation and reconfirms the applicability the equation in high salinity range.

To overcome the limitations of misfit of conductivity data

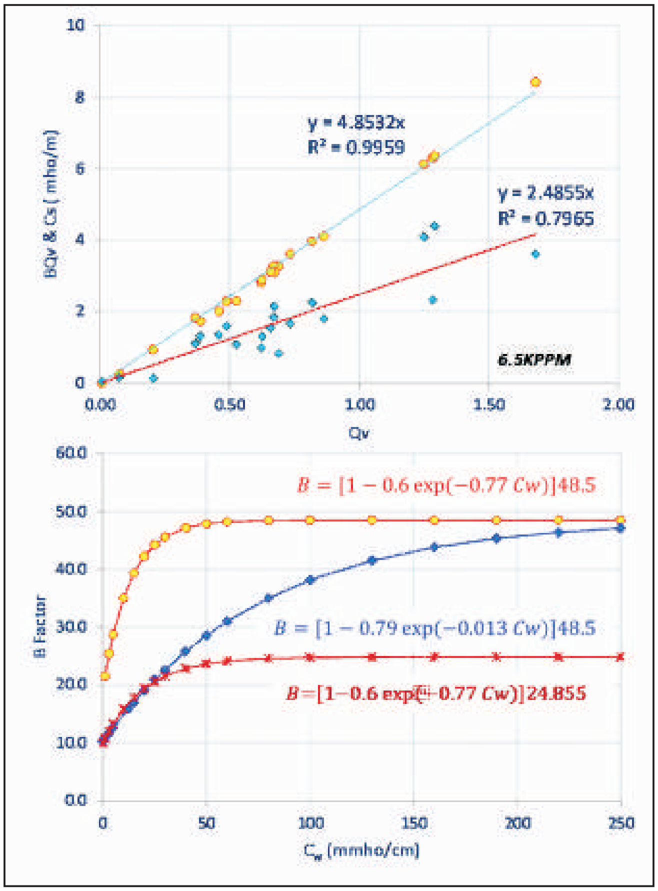

Fig. 3: Derivation of B_{max} factors using least square fit in high and low salinity data and respective B functions (red curves) derived with WS equation. Modified B function satisfying both high and low salinity data is indicated in middle as blue curve

in low salinity, process of estimation of average value of *B* was repeated with actual surface conductivity calculated as difference between rock conductivity and solution conductivity i.e. $C_s = C_o F^* - C_w$. Low salinity conductivity data have been found to be showing excellent fit with correlation coefficient in range of *80-94*. New average *B* values of *24.855* and *23.387* $mho\ cm^2 equiv^{-1}$ have been derived from actual surface conductivity. New value of minimum limiting *B* value, B_{min} is estimated to be consistently *10* in all low salinity measurements of both wells.

Extrapolation to zero conductivity using Waxman-Smits empirical equation is resulting in a calculated value of *10* for equivalent ionic conductance of the sodium exchange cations associated with a kaolinite/ quartzitic siltseems to be justified as compared to *18.4* for montmorillonite well known as clay type with highest cation exchange capacity, matching value of which also been derived by nonlinear exponential regression of Waxman-Smits data sets in low salinity region.

New *B* function derived with low salinity measurements show excellent fit only for low salinity data salinity data with consistent departure in case high salinity data. Following three modified equations for *B* as function of solution conductivity have been proposed which show excellent fit of conductivity data in low as well as high salinity measurements respectively for *6.5, 100, 200 kppm* data set in first well and *8, 100, 200* and *13.8, 100, 200*kppm data sets in second well as indicated in Figs 4, 5 and 6.

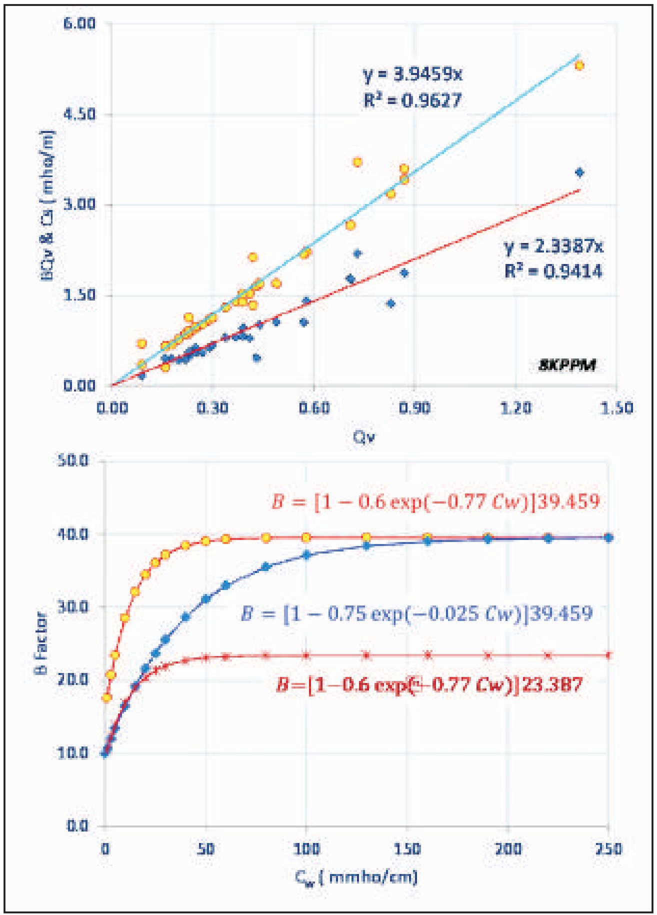

Fig. 4: Derivation of B_{max} factors using least square fit in high and low salinity data and respective B functions (red curves) derived with WS equation. Modified B function satisfying both high and low salinity data is indicated in middle as blue curve.

$B=[1-0.79\ Exp(-0.013\ C_w)]48.5$..........................I

$B=[1-0.75\ Exp(-0.025\ C_w)]39.459$...................... II

$C_w=[1-0.75\ Exp(-0.025\ C_w)]40.215$.................... III

Finally, theoretical C_o values at different C_w are computed using known values of F^* and Q_v values using Waxman-Smits equation for varying values of Q_v with constant *B* factor computed at particular brine conductivity.

Validation of modified Waxman-Smits conductivity relationship

Validation on C_o-C_w Curves

A comparison of conductivity curves derived from available electrical core measurements with theoretically derived curves for Waxman and Smits model are presented in Fig-6 for *6.5*kppm salinity core measurements of the plugs of

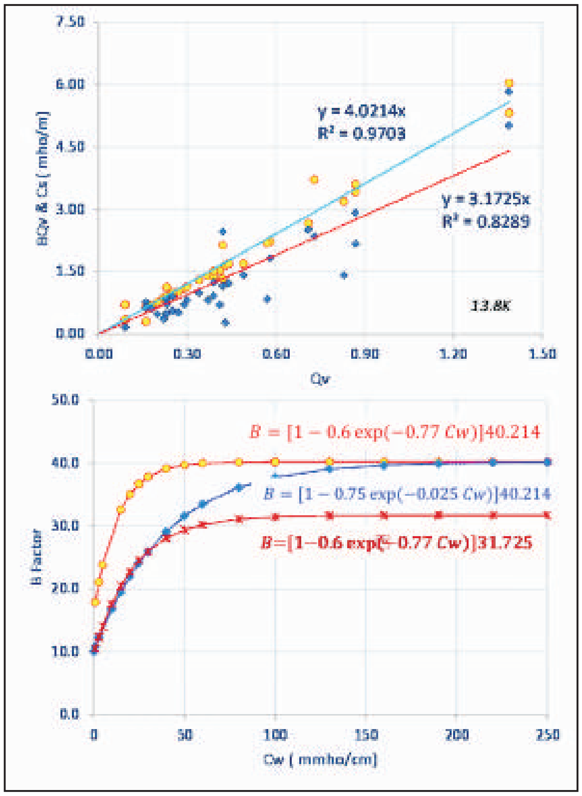

Fig. 5: Derivation of B_{max} factors using least square fit in high and low salinity data and respective B functions (red curves) derived with WS equation. Modified B function satisfying both high and low salinity data is indicated in middle as blue curve.

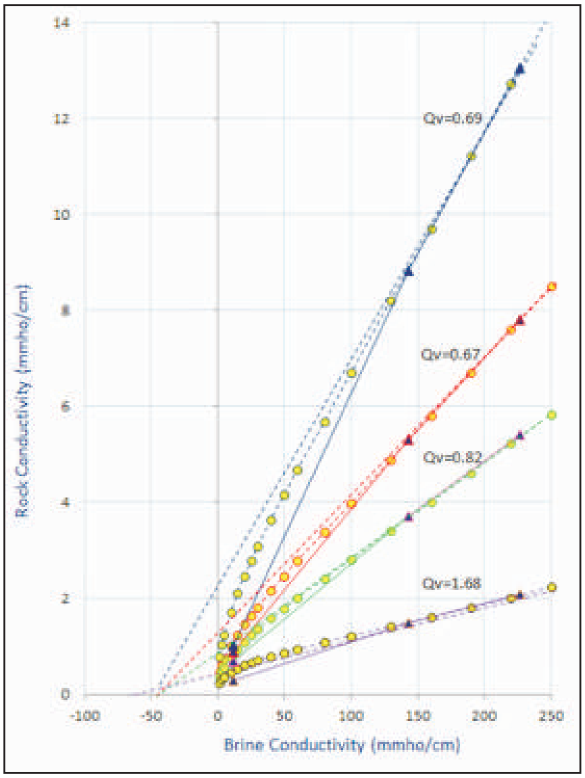

Fig. 6: Deviations of theoretical conductivity curves derived from Waxman-Smits approach and measured conductivity for few 6.5 kppm salinity data set with varying Qv values

Q_v values varying in the ranges of *0.67-1.68*. Core measurements clearly indicate that the plugs with lower as well as very high Q_v values do not conduct through WS model shaly sand mechanism.

Comparison of conductivity curves derived from available electrical core measurements with theoretically derived curves for modified WS model are presented in Fig-8 for the core data set presented in Fig-7. New conductivity curves are showing excellent match with actual core measured data for the low as well as high salinity regions.

Validation of Surface Conductivity in Fully Water Saturated State

Surface conductivity has been directly derived from core measurements as $C_s = C_o F^* - C_w$. Comparison of surface conductivity from electrical core measurements and respective values derived from WS model (*BQv)* and newly modified WS model (*BQv_new)* are respectively presented in Fig-8 respectively for *6.5* (blue triangle) and *8*(yellow circles) kppm salinity core data sets. Values derived from newly modified WS model are showing good match with actual values as compared to the Waxman-Smits model derived values in Fig-8. Scatter on plots are increasing with decreasing of salinity in these plots. It indicates the subjectivity of applicability of the model with decrease of salinity.

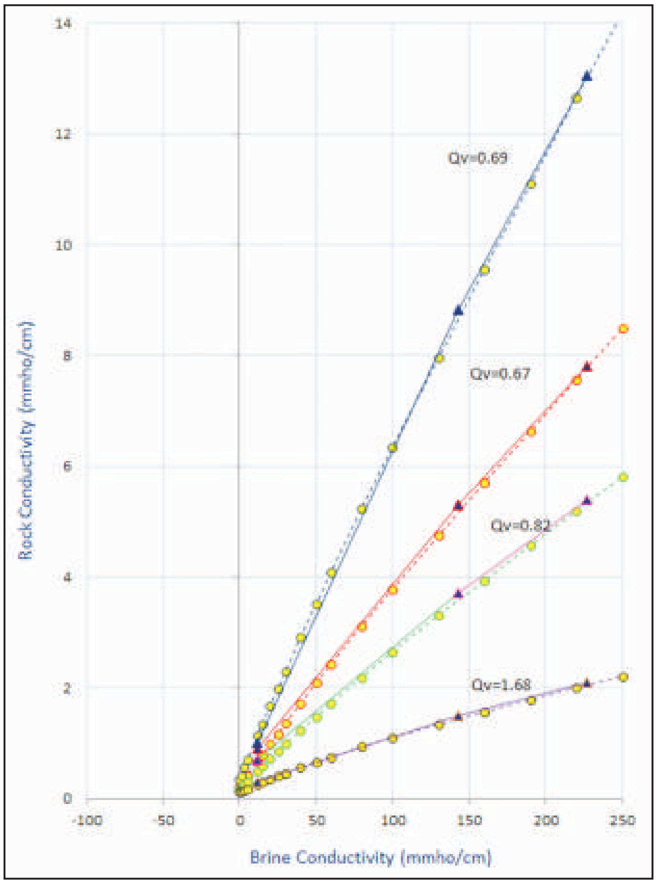

Fig. 7: Comparison of theoretical conductivity curves derived from modified Waxman-Smits approach and measured conductivity values for few 6.5kppm salinity data set with varying Qv values

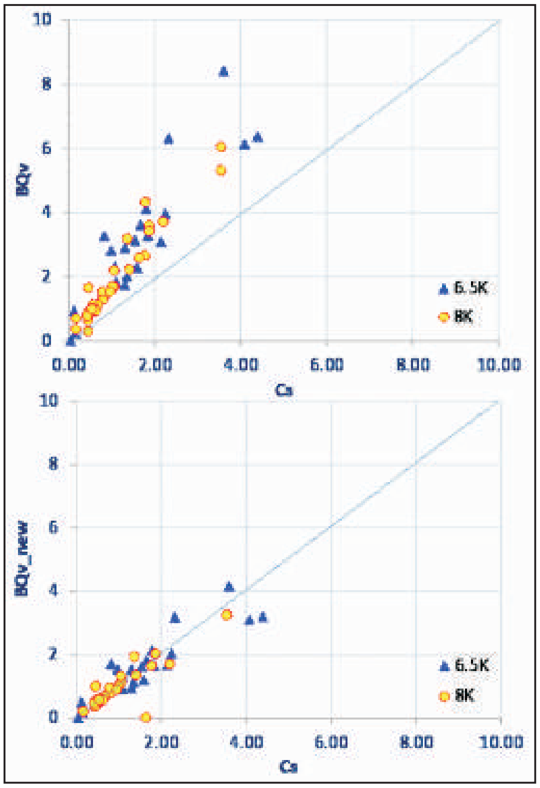

Fig. 8: Correlation of core measured surface conductivity with WS model and modified WS model derived values of 6.5 and 8 kppm data sets.

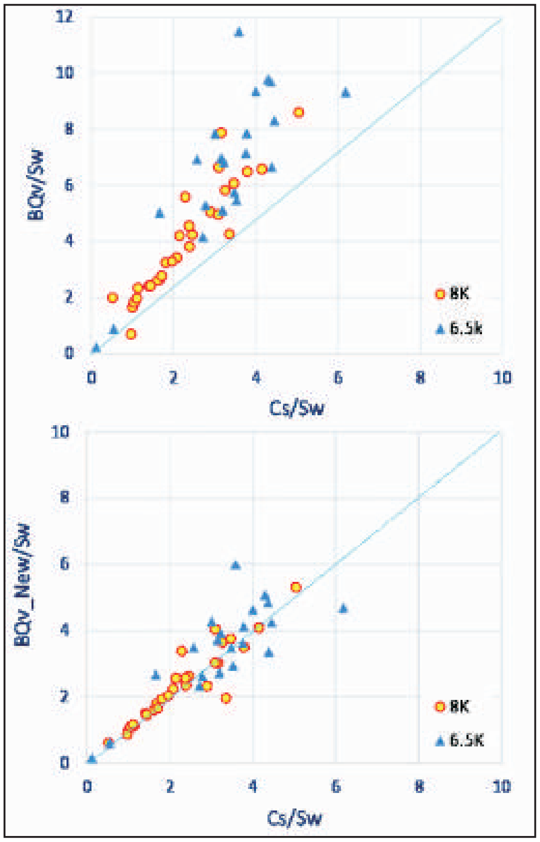

Fig. 9: Correlation of core measured surface conductivity with WS model and modified WS model derived values of 6.5 and 8 kppmdata sets in partially saturated state.

Validation of Surface Conductivity in Partially Water Saturated State

In case partially saturated state, surface conductivity has been directly derived from core measurements as $C_s = C_t G^* - C_w/S_w$. Comparison of surface conductivity from electrical core measurements and respective values derived from WS model (BQ_v) and newly modified WS model $(BQ_v_new)$are respectively presented in Fig-9 respectively for *6.5* (blue triangle)and *8*(yellow circles)kppm salinity core data sets.

Values derived from newly modified WS model are showing good match with actual values as compared to the Waxman-Smits model derived values in Fig-9. Scatter on plots around 45 degree lines has also been reduced.

Validation of Excess Conductivity in Fully Water Saturated State

Formation factor ratio or reduction in apparent formation factor with respect to its intrinsic or clay corrected value, $F^*/F = (C_w+BQ_v)/C_w$ is a measure of excess conductivity in shaly sand rocks. Core derived values of F^*/Fhave been compared with predicted values from WS and modified WS models are respectively presented in Fig-10 and 11 respectively for (*6.5, 100 and 200) and* (*8, 100 and 200)*kppm salinity core data sets as indicated with legends. Values derived from newly modified WS model are showing good match with actual values as compared to the Waxman-Smits model derived values. Scatter on plots around 45 degree lines has also been reduced. It indicates the reduced subjectivity of applicability of the modified WS model.

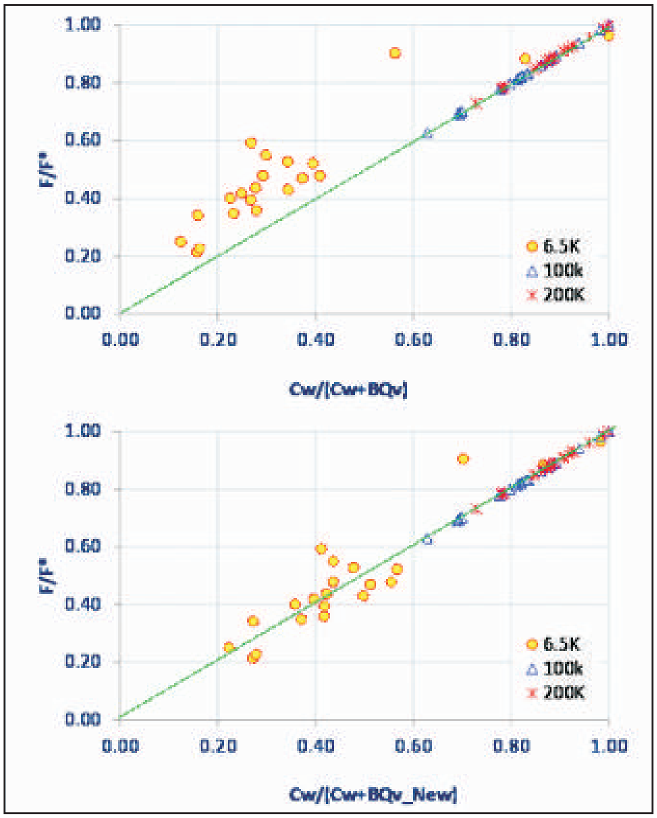

Fig. 10: Correlation of core measured excess conductivity with WS model and modified WS model derived values of 6.5, 100 and 200 kppm data sets.

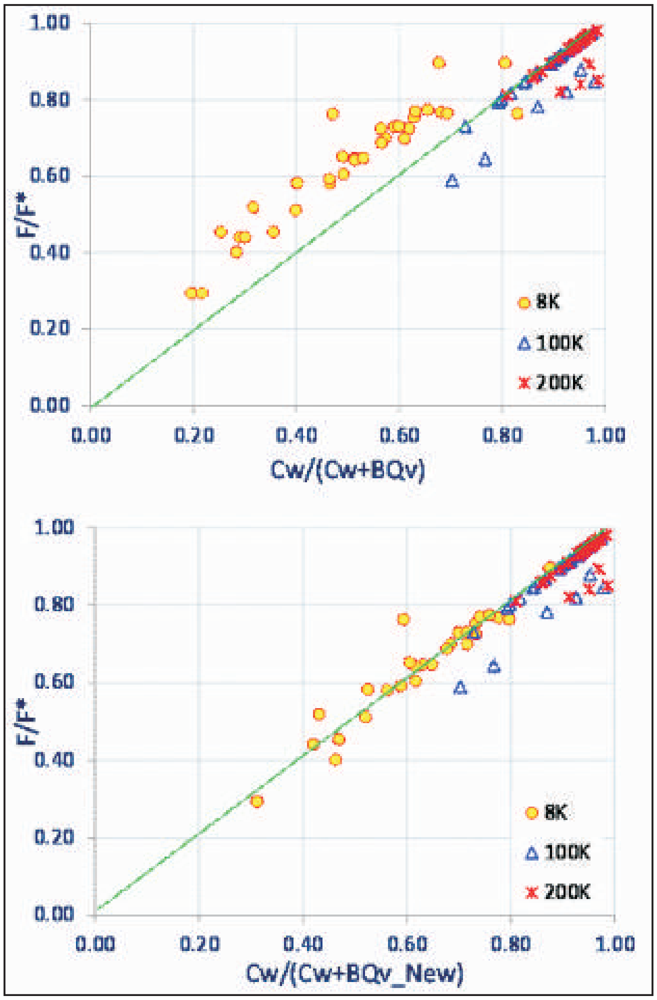

Fig. 11: Correlation of core measured excess conductivity with WS model and modified WS model derived values of 8, 100 and 200 kppm data sets.

Validation of Excess Conductivity in Partially Water Saturated State

Generalized formation factor ratio or reduction in apparent formation factor with respect to its intrinsic or clay corrected value, $G^*/G=(C_w+BQ_v/Sw)/C_w$ is a measure of excess conductivity in shalys and rocks. Core derived values of G^*/G has been compared with WS and modified WS models are respectively presented in Fig-12for *6.5 and 8*kppm salinity core data sets as indicated with legends.

Values derived from newly modified WS model are showing good match with actual values as compared to the Waxman-Smits model derived values in Fig-12. Scatter on plots around 45 degree lines has also been reduced. It indicates the reduced subjectivity of applicability of the modified WS model with new *B* values. This provides the basis for validity of using new equation in partially saturated reservoirs.

Discussions and Conclusions

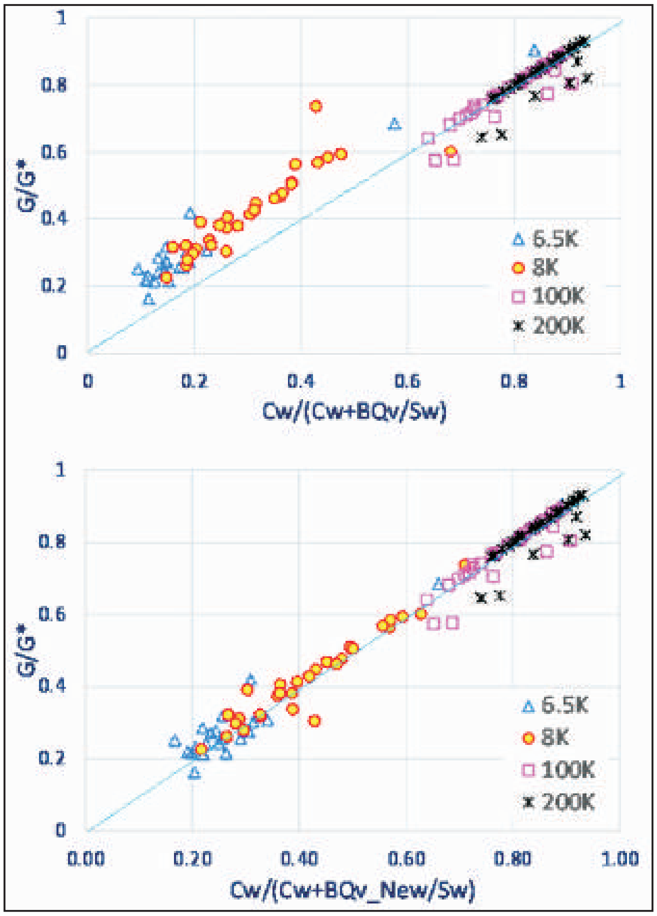

Fig. 12: Correlation of core measured excess conductivity with WS model and modified WS model derived values of 6.5 and 8 kppm data sets in partially saturated state.

Archie equation has been modified and expanded to explain- resistivity measurements over a wide range of rock formations. More than fifty derivatives, mostly empirical, of Archie's original equation exist to address the complex problem of shaly sand water saturation (Patnode and Wyllie, 1950; Winsauer and McCardell, 1953; Wyllie and Southwick, 1954; Waxman and Smits, 1968; Poupon and Leveaux, 1971; Bussian (1983), Clavier et al., 1977; Herron, 1986; Sen et al., 1988; Schwartz and Sen, 1988, Revil et al, 1998). The reason for this proliferation is that people try to change a previously existing scheme when it fails for a particular formation. Most of the formulae are based on empirical observation and often it is not clear where the limitations of those formulae are.

Waxman-Smits model has become the most fully developed and widely accepted approach to the understanding of electrical conductivity of shaly sand formations with high salinity as it adequately reduce uncertainty in hydrocarbon saturation estimates. Although, it is a very simple equation, $C_o = (C_w + BQ_v)/F^*$, with sound physical and mathematical basis, there are number of limitations associated with it (Bussian,1983; Yuan, 1991):

- In clay-bearing rocks, if the conductivity of clay is smaller than the conductivity of brine, the Waxman-Smits assumption of a constant *F** is valid. However, where the conductivity of clay exceeds the conductivity of brine, *F** may no longer be constant, implying that the Waxman-Smits assumption of a constant *F** is not always valid.

- Waxman or Dual water models are based on an assumption that the co-ions and counter-ions are affected by the same tortuosity, or a volume average applies to the surface and bulk conductivity, which is true only in the very simple geometry of a straight tube, and is not true in general for porous medium.
- Even for the linear regime in the C_o-C_w, plots, the analytical results show that the bulk rock conductivity is more complex than a simple volumetric average, as assumed by Waxman and Smits (1968) and by Clavier et al. (1977). In fact, the dc conductivity depends not only on the clay proportion itself, but also on clay type and on its distribution through the rock.
- Waxman-Smits, Dual water and other cation exchange related models are primarily based on the Waxman and Smits (1968) data which used only *NaCl* electrolyte solutions. Other ions, especially calcium, produce smaller clay conductivity effects. Thus *CEC* techniques for estimating '*B*' will be limited inaccuracy in cases where reservoir formation brine does not correspond to sodium chloride.
- The cation mobility factor, *b* in the dual water model is also based on the same database as Waxman and Smits, and hence its value is well defined only for the specific case of reservoirs with sodium chloride as the formation brine (Hardwick (1987).

On a plot of conductivities of saturating water, C_w and fully saturated rock, C_o positive cutoff on C_o necessarily represents deviations from Archie's conditions. It is only sufficiently large value of negative cutoff on C_w computed through extrapolation, which verify for the electrical conduction through shaly sand mechanism C_c. Sufficient value of C_c has to be verified for shaliness on multiple salinity electrical core measurements. Relatively cleaner rock samples of fluvial reservoirs exhibit large values of cutoff on ordinate, excess conductivity, *Cr* computed through extrapolation of high salinity linear trend and seem to have the apparent electrical conduction somewhat similar or even more as compared to shaly sand mechanism as indicated in Fig-7. One of the reasons for failure was the application of shaly sand interpretation model without applying any criteria of verifying suitability of the model in fresh water fluvial reservoirs in low salinity region, sometimes even without confirming the presence of high *CEC* clays like montmorillonite. Absence of high *CEC* clays in fluvial reservoirs leads to lower F* and lower value of BQ_v values. The cation mobility factor, *B*, in the WS model is based on the shaly sand core data sets of Hill and Milburn (1956), and hence its value is well defined only for the specific case of reservoirs with high *CEC* clay showing higher limiting value of 18.4 at $C_w=0.0$.

Basic nature of conductivity curve is controlled by this function. Value of multiplication factor *B* does not depend on *Qv*. Its value exponentially increases with water conductivity in lower salinity range up to a limiting value B_{max} after which it becomes constant in higher salinity. Excess curvature introduced by surface conductance phenomenon particularly in the higher salinity range results in a lower slope of the line in this range with higher positive cut off C_r in case of clean sand. This gives false impression of clean layers of fluvial reservoirs appearing more shaly or conducting on C_o-C_w plots leading to the over prediction of surface conductivity as shown in Fig-9.

Reduction in formation factor particularly at lower salinity measurements generally corresponds to the exponential decrease of *B* with decrease of C_w in lower salinity range as shown in Fig-1 (Waxman-Smits, 1968). In the lower salinity range as C_w becomes smaller, slope of curve is governed by term *BQv/F**. Multiplication factor *B* will produce same rate of change for clean with lower *Qv* as well as shaly layers with higher *Qv*. Reduction in formation factor will be same in both cases as indicated conductivity curves for the rock samples from fluvial reservoirs. Change of slopes of conductivity curves in the ranges of low and high formation water conductivities/salinities for relatively clean as well as for shaly samples are more or less similar. Relatively clean refer to the rock samples with some nominal value of shaliness or *Qv*.

Waxman and Smits (1968), Clavier et al (1984), found a strong correlation between the exponent *m** and clay content. This would suggest that the tortuosity of shaly sand is much greater than that of clean sands. It means *F** will be higher in case of shaly sand as compared to clean sand. However, increase of *F** always may not be associated with shaliness. The ratio *F/F** is an electrical measure of departures from Archie's conditions, it is not an electrical measure of shaliness (Worthington, 1991). So, attributing the decrease of apparent formation factor *F*, at lower salinity as compared to *F** to the shaliness without verification on the value of C_r and $C_c$on C_o-C_w plot, may be misleading and far from reality.

Clay excess conductivity shift becomes non-linear toward the origin because the excess conductivity associated with the clays predominates in the relative absence of free ions in the increasingly fresh formation water. An essential requirement of any empirical models is to capture such a nonlinear (convex-upward) behavior of the C_o curve at low values of salinity. The WS model captures this behavior by allowing the counterion mobility, *B*, to increase exponentially at low values of C_w until it attains a constant and maximum value at high values of salinity. Using a diffusion current model, Sen (1987) demonstrated that the nonlinearity of C_o-C_w follows naturally as a consequence of distribution of electric field between the two regions. Revil et al. (1998) suggested an effective medium theory that accounts for the different behavior of anions and cations in the two conductive regions. Bussian (1983) proposed a general model describing conductivity of heterogeneous mixtures and then applied a similar theory to describe the electrical conductivity of shaly sands.

A comparison of electrical conductivity data of fluvial reservoirs with Waxman and Smits shaly sand samples measurements clearly showing large deviation from high salinity trend line in low salinity region even with similar values of volume concentration of clay exchange cations, *Qv* and B_{max} values closely agreeing with WS model. However, WS samples in low salinity region are showing little or nominal deviations from high salinity linear trends. Fresh water fluvial low salinity conductivity data have been found to be showing fit with good correlation coefficient and new value of minimum limiting value of B is estimated to be close to *10* in both wells. With this lower bound, modified B as function of solution conductivity show excellent fit of conductivity data in low as well as high salinity regions in fresh water fluvial reservoirs. Nearly half of the lower bounds in fluvial reservoirs as compared to the WS model based on very high CEC, montmorillonite clays, seems to be justified in case of fluvial reservoirs with predominantly lower CEC kaolinitic clays. Predicted values of surface conductivity C_s, F/F^* and G/G^* have been found to be close agreement with respective core measured values with different salinity in fully as well as partially saturated reservoirs. This provides basis for applicability modified WS equation hydrocarbon saturation. Due to non- availability of such modification in WS equation in commercial packages, application to the field examples of log data processing results could not be presented for the time being.

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Nomenclature

B	equivalent conductance of clay exchange sodium cations as function of $C_{w\,at}$ *25 C,* mho sq cm meq^{-1}
C_o	conductivity of fully water-saturated rock (mho/m or mmho/cm)
C_r	conductivity of rock matrix (Sm^{-1})
C_t	conductivity of partially water-saturated rock (Sm^{-1})
C_w	conductivity of formation water (Sm^{-1})
R_o	resistivity of fully water-saturated rock (Ohm-m)
R_t	resistivity of partially water-saturated rock (Ohm-m)
R_w	Resistivity of formation water (Ohm-m)
F	formation factor
F^*	intrinsic formation factor
G	generalized formation factor
G^*	intrinsic generalized formation factor
I_r	resistivity index
I_r^*	intrinsic resistivity index
Q_v	cation exchange capacity per unit pore volume (equiv. liter^{-1})
S_w	water saturation
m	porosity exponent
m^*	intrinsic porosity exponent
n	saturation exponent
n^*	intrinsic saturation exponent
C_c	scaled non-Archie conductivity (Sm^{-1})
	fractional porosity

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