Electrical Characterization of Low Resistivity Fresh Water Fluvial Reservoirs of Krishna Godavari Basin, East Coast, India*

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Abstract

Determination of hydrocarbon saturation in low resistivity 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 severely non-Archie behaviour of electrical conduction where conventional shaly sand equation breaks down. This is mainly due to the small grains/pores with large surface areas exhibiting excess surface conduction in low salinity similar to clay/shale. Anomalous reduction of formation resistivity factor against fine grained/micro-pores is directly related to tortuosity or cementation exponent for a particular salinity, as pore volume (porosity) is nearly constant and does not change with grain size.

Pseudo-Archie method has been used for precise computation of water saturation in these reservoirs where reduction of cementation, '*m*' and saturation, '*n*' exponents are allowed to find their own levels to take care of anomalous reduction of formation resistivity factor. Severely non-Archie reservoirs are indicating linear relationship of cementation exponent with excess conductivity on core measurements, which in turn related with the shale/silt volumes. For the compensation of excess conductivity related with surface conductance phenomenon a relation has been developed, which allow 'm' to change from '*m*' clean sand to '*m*' shale, as a function of shale volume.

In this paper, experimental basis has been evolved for the compensation of additional conduction with respect to Archie through a large number of geological and multiple salinity electrical core measurements of a completely cored reservoir section. Excess surface conductance phenomenon is identified on formation factor ratio with brine conductivity plot derived from these measurements. A linear regression of the data points in water bearing zone of the reservoir indicate volumetric average relationship, where cementation factor varies between the respective values of clean sand and shale beds. In hydrocarbon zone, use of Archie bound water exponent *mn* (=*m*=*n*) instead of m and n significantly improves the correlation coefficient with reduced standard error. The results of extensive laboratory experiments, described in this paper, show that the use of variable exponents approach to characterize electrical behaviour of fluvial reservoirs is substantially better than the conventional use of an average value and corroborates well with core derived water saturation.

Introduction

Precise estimation of water saturation in low salinity 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 severely non-Archie behaviour of electrical conduction. When the reservoir brine is relatively fresh, the evaluation problem is compounded because the effect of grain size/clay in proportional to the resistivity of the brine.

Unlike high salinity formations water, where the electrical currents is conducted through the pore fluid, in fresh water the electrical current appears to be conducted along the grain-aqueous interface by surface conductance rather than through grain or pore fluid. Formation factor increased in fresh water solutions as the mean grain diameter increased opposite of the relationship normally found in formations saturated with high salinity water. Many investigators have noted that the apparent formation factor of porous materials will diminish as the interstitial water becomes relatively fresher (Patnode and Wyllie, 1950, Winsauer and McCardell, 1953, Hill and Milburn, 1956, Evers and Iyer, 1975). This effect has been attributed both to conductive solids (shale or clay) and to the existence of a concentrated layer of ions adsorbed on the surface of the rock matrix. The large surface areas associated with clay and shale merely enhance the effect of surface conductance when these materials are present. Sarma and Rao (1963) have demonstrated excess conductivity with fresh water sands without the presence of any clay or shale.

Alger (1966) conducted a number of laboratory experiments demonstrating that the formation factor, F increased in fresh water solutions as the mean grain diameter increased opposite of the relationship normally found in brine saturated formations i.e. Archie (1942) Law. The length of the current path is directly related to the shape, diameter and sorting of the grains, geometric arrangement and degree of matrix cementation. All of these factors that serve to increase the current path length (and formation factor, F) also are important factors in increasing formation permeability (Kwader, 1985). The surface conductance is influenced by grain size, grain packing, grain sorting and cementation (m). The cementation exponent ‘m’ is not only dependent upon the degree of cementation between the grains but also the size, shape and sorting of the grains, type of packing arrangement between the grains, and can be directly related with F.

In this paper, electrical characterization of low salinity fluvial reservoirs of KG Basin, East Coast of India, has been presented based on large number multiple salinity electrical core measurements. Excess conductivity based rocks classification indicates that majority of reservoir rocks conform to non-Archie conditions in the fully water saturated state but show pronounced departures from non-Archie conditions in the partially water saturated state. Precise computation of water saturation in severely non-Archie reservoirs requires a pseudo-Archie method where reduction of cementation ‘m’ and saturation ‘n’ exponents are allowed to find their own levels to take care of anomalous reduction of formation resistivity factor. A generalized least square relationship to account for the surface conductance associated with grain size has been evolved through linear regression analysis in known water bearing zones of the reservoirs. ‘m’ is varying from clean sand to shale volume as volumetric average, where ‘m’ for clean sand to shale is close to two and one respectively. A new approach has resulted in a realistic evaluation of low resistive reservoirs corroborating with the available core measurements and testing results and will be very useful to delineate low resistive reservoirs.

Excess Conductivity Based Rock Classifications and Applicability of Water Saturation Equations

Reservoir rocks are classified based on excess electrical conductance mechanism to know the applicability of Archie's or shaly sand or pseudo Archie equation in case of severely non-Archie reservoirs (Worthington, 2006). An extra conductivity term $x = X/F^*$ has to be added to accommodate the additional non-Archie conductivity based on Waxman-Smits (1968) as $C_o = C_w / F^* + X/F^*$, Where 'x' represents rock conductivity in excess of water and is defined as intercept on Co when conduction through fluid is zero i.e. $C_w=0$. Excess conductivity can be related in terms of ratio of Intrinsic or clay corrected formation factor F* and reduced apparent formation factor F in case of non-Archie reservoirs. $C_w / F = C_w / F^* + X/F^*$ or $F^*/F = (C_w + X) / C_w$

Reservoir rocks are classified as per excess conductivity (F^*/F) respectively in fully and partially water saturated conditions as;

- Archie rocks when F/F^* or $G/G^* >= 0.9$
- Non-Archie rocks or shaly sand with $0.5 < F/F^*$or $G/G^* < 0.9$
- Severely non-Archie rocks with F/F^* or $G/G^* < 0.5$

Multiple salinity measurements of core data are presented in Figure 1. Shifting of nature from Archie to non-Archie nature related with increase of surface conductance is evident with decrease of salinity as well as water saturation. All the core plug measurements are indicating a shift in the nature of shaly sand reservoir in fully water saturated condition to a severely non-Archie nature in partially saturated condition. Pore fluid effect is more pronounced at lower salinity measurements.

Worthington, 2006, proposed application of pseudo Archie method for the computation of realistic water saturation in low resistive fluvial reservoirs. The method is based on derivation of apparent values of *m* and *n*. It is 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 $G/G^* = \phi^{m^* -}\,\mathrm{m}\,S_w^{n^* - n}$ to make an estimate of n, and vice versa. Again, core measured '*m*' and '*n*' parameters are needed for validation of accurate Petrophysical evaluation. Moreover, presence of clays deviates the clay corrected or intrinsic values of these parameters and does not allow to start with default values of $m^*= n^*=2.0$. It is quite cumbersome to classify, compute and apply the varying values of 'm' and 'n' for the quality assured evaluation of hydrocarbon of reservoirs due to higher vertical heterogeneity. The method suffers the limitations of shale/clay corrected parameters as in case of Waxman-Smits Model (1968).

Correlation of Cementation, Saturation and Bound Water Exponents with Excess Conductivity

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. Many relationships become simplified by using Archie bound water exponent, $mn=m=n$ as compared to the exclusive use of m and n core log integration. It is evident that *mn* with good highest correlation seems to be the most appropriate to model excess conductivity *G*/*G** in hydrocarbon zone as indicated in Figure 2. Decreasing of '*mn*' is resulting in decrease of formation resistivity factors in aquifer as well as generalized formation factor in partially saturated rocks.

Derivation of m from Regression Analysis of Core and Log Data

Regression analysis of Core derived '*m*', in case of fully water-saturated conditions, with *Vshale* LPSA measurements are presented in Figure 3. Similar relationship is also derived from log measured values of m with *Vshale* derived grain size index i.e. neutron density log separation in aquifer. These linear relationship are just interpolation between two ends defined as *Vshale* = 0.0 and 1.0. Composite value of 'm' can defined as volumetric average of end facie values derived from boundary conditions as *m_sand* when *Vshale* =0.0, and *m_shale* when *Vshale* =1.0 in the equation:

$$m = m\_sand * Vsand\_ND + m\_shale * Vshale\_ND$$

The core data represents only small part of the log data. Therefore, the total comparison of core data and log data is not possible. Similar regression analysis in partially saturated conditions shown in Figure 4, indicates variation in mn value in both sand and shale i.e. *mn* =1.8 in clean sand and 0.7 for shales from log data whereas *mn*=1.77 and shales *mn*=1.14 for core data. Boundary conditions are matching in clean sand beds as core data represents facies with 0-16% of shaliness only. Other end 16-100% can only be seen on logs in shale beds as marked pink color in Figure 4.

Discussions and Conclusions

In clean sands with saline pore fluid in insulating matrices, accuracy of Archie's equation is well established. Where salinities are relatively high conventional shaly sand equations adequately reduce uncertainty in hydrocarbon saturation estimates. 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). Application of pseudo Archie method with apparent '*m*' and '*n*' values linked with apparent formation resistivity factor take care of all type of surface conduction mechanism irrespective of lithology, whether it is due to clays or smaller very fine sand particles. 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. Brown, 1986, developed an equation, which was an expansion of dual water model concept to allow '*m*' to change from '*m*' clean sand to '*m*' shale, as a function of shale volume.

Analysis of core data in terms of the Conducting Rock Matrix Model (Givens, 1986) shows that saturation exponent *n* and the porosity exponent '*m*' are not independent rock parameters but are both dependent on the complexity of the tortuous pore-fluid network within a rock. Where rock grain surfaces are water wet there is justification to equate '*m*' an '*n*' since both are exponents of functions which describe formation water distribution within the rock system.

A least square relationship between ‘*m*’ and shale volume/grain size index has been evolved through linear regression analysis in this paper for fluvial reservoirs, as surface conductance phenomenon does not differentiate between clay and very fine sand/silty particles. It is equation with variable ‘*m*’ and ‘*n*’, which allows varying these parameters respectively from clean sand to very fine/silty shale, as a function of shale volume. Value of ‘*m*’ less than or equal to unity in shales indicates micro porosity providing direct path to electrical currents without any tortuosity along with surface conductance phenomenon. This has resulted in a unified equation, which covers entire spectrum of Archie, non-Archie and severely non-Archie 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 (Figure 5).

Acknowledgments

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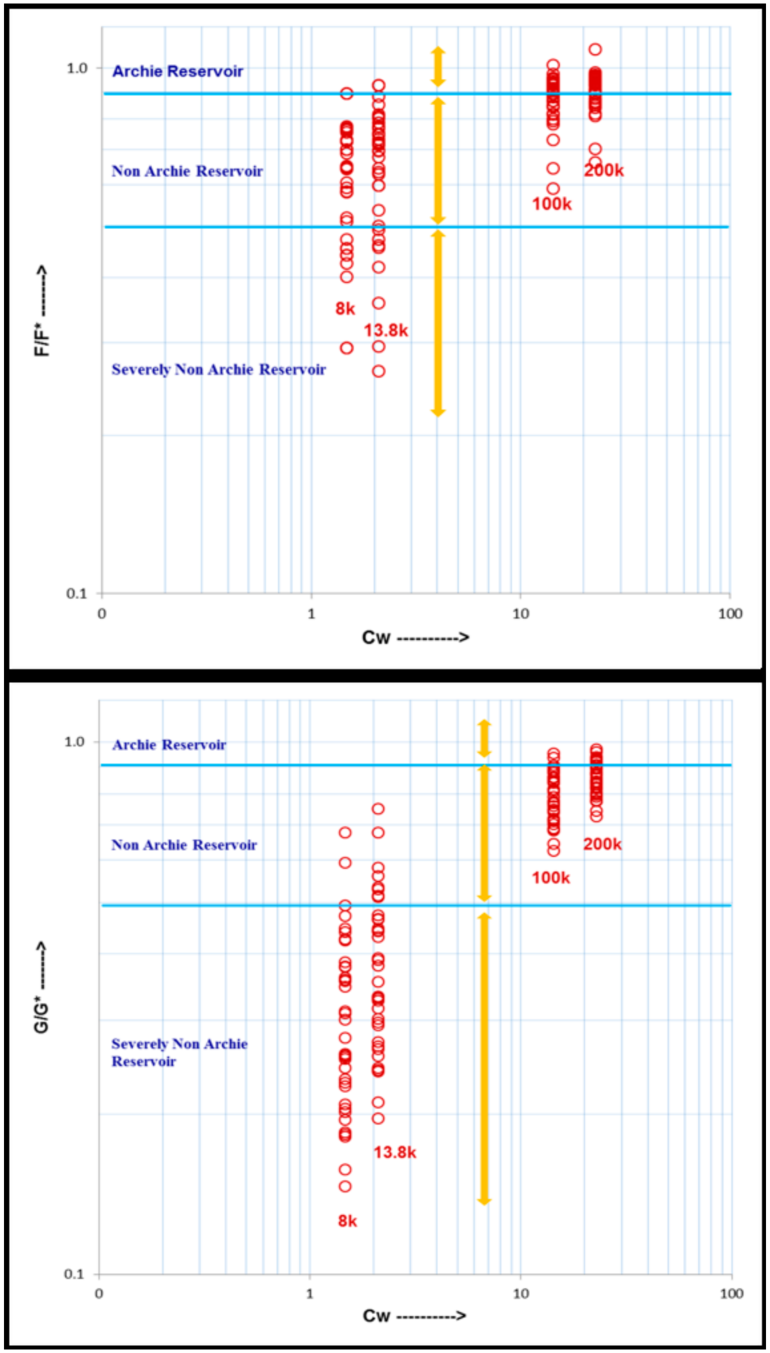

Figure 1. Classification of Reservoirs.

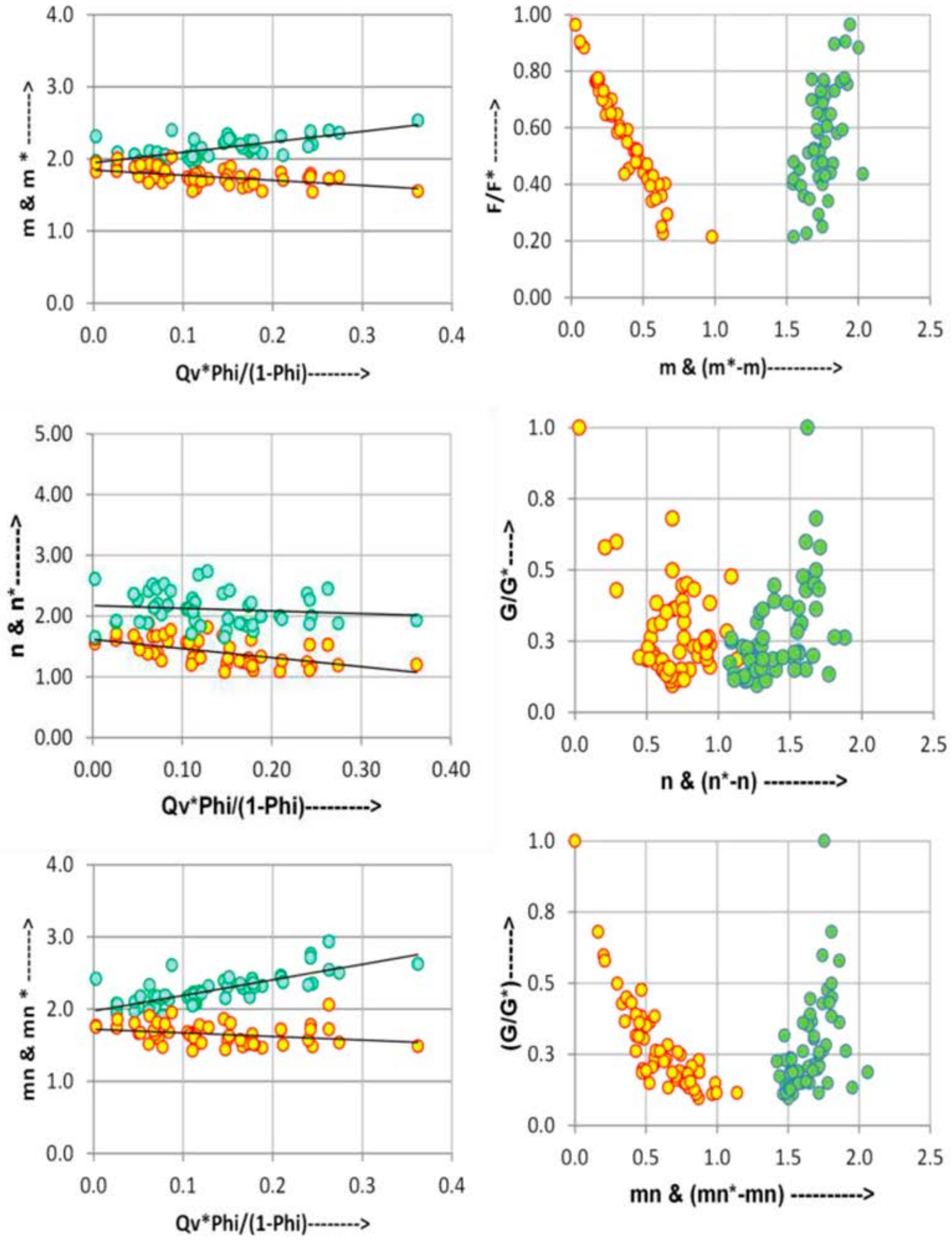

Figure 2. Linear Relationships of apparent and intrinsic values of m, n and mn with excess conductivity.

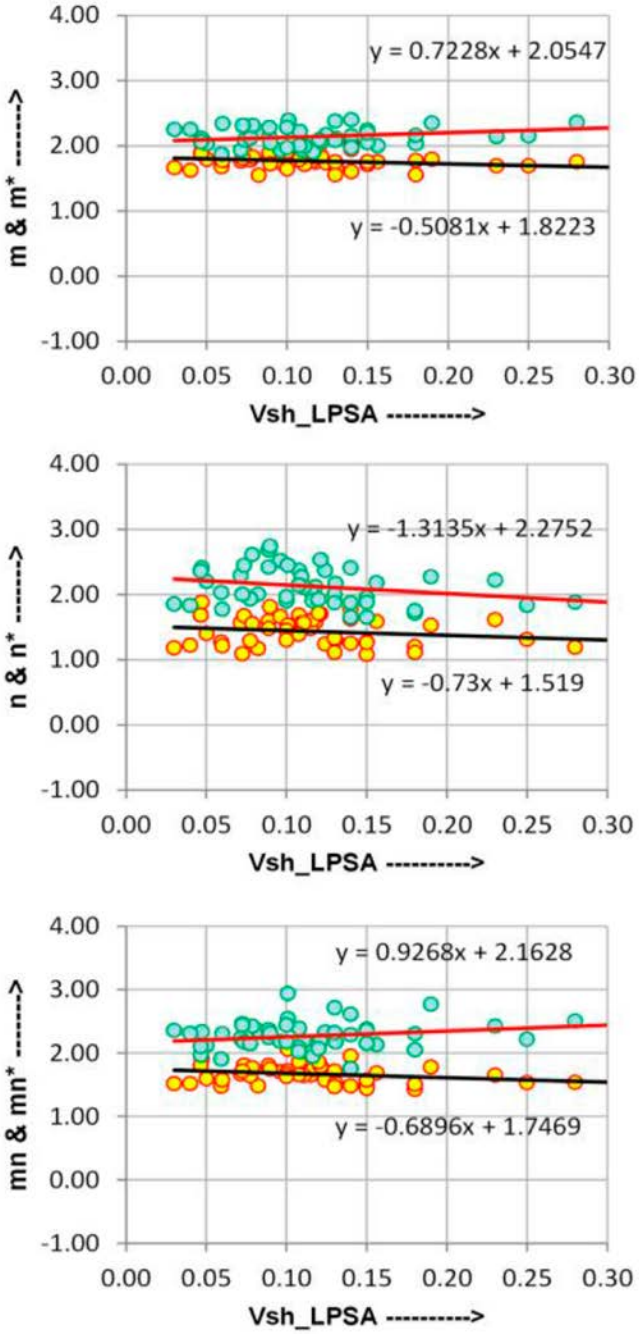

Figure 3. Data showing Linear Relationships of apparent and intrinsic values of m, n and mn with shaliness Classification of Reservoirs.

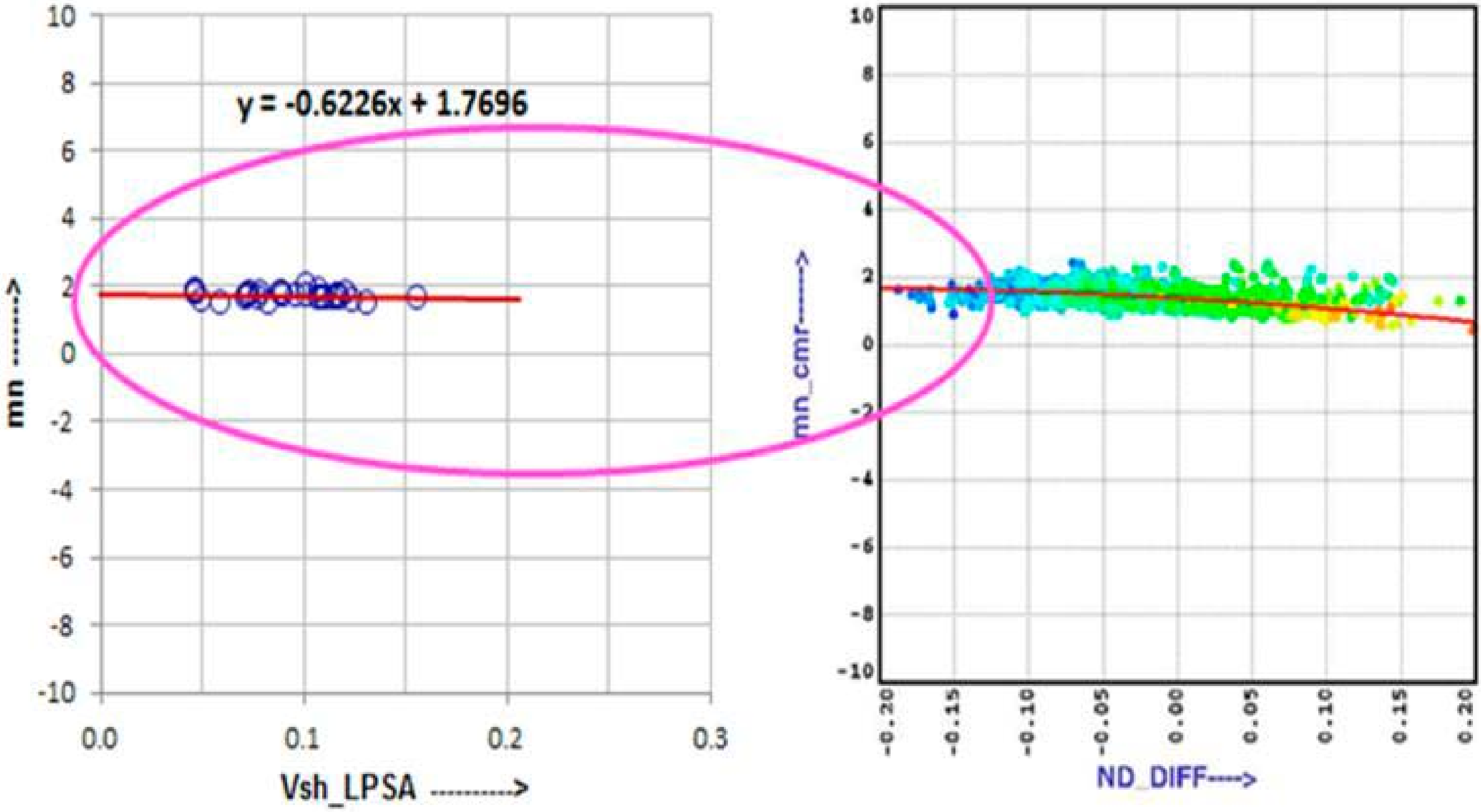

Figure 4. Derivation of mn from Regression analysis of Core and Log data in hydrocarbon zone.

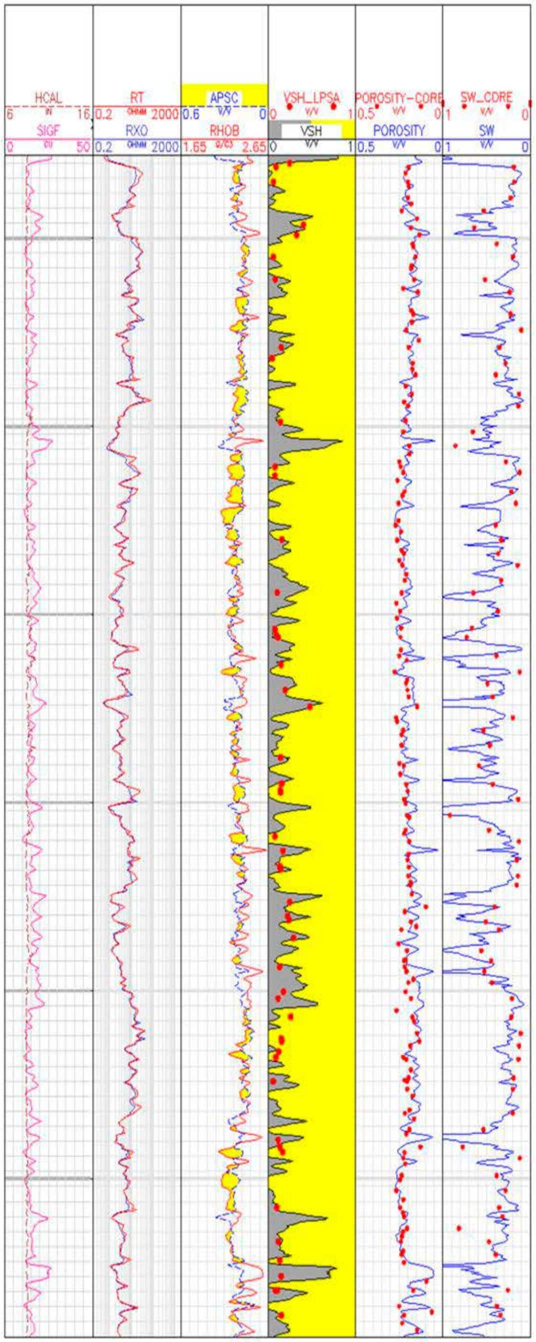

Figure 5. Validation of processing results with CMR and core data.