Definitive interpretation models derived from covariance of log motifs for the realistic evaluation of fresh water tertiary reservoirs of Upper Assam, India

*Lalaji Yadav**
E&P Business, Reliance Industries Limited, RCP, Ghansoli, Navi Mumbai- 400701, INDIA
lalaji.yadav@ril.com

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Abstract

Determination of hydrocarbon saturation in fresh water tertiary reservoirs of Upper Assam, Basin 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 behavior of electrical conduction, where conventional shaly sand equation breaks down. This is mainly due to very large facie variations associated with varying grain sizes and presence of mica or combination of feldspars and heavy minerals in addition to quartz and clay. 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. Formation water exhibits a very large variation of salinity from ~1.0 kppm in Tipam Sand-1 to ~10 kppm in Sylhet/Kopili formations. Whether variation on resistivity is predominantly controlled by water volume or change of formation resistivity factor, it has to be ascertained beforehand through visual correlation on log motifs. Principal benefits of co-variances of log motifs has been the identification of presence or absence of surface conductance phenomenon associated with grain size variations followed by application of appropriate model for water saturation estimation in these reservoirs.

Pre-knowledge about the conductivity behavior of the matrix, particularly silt and pseudo silt, in addition to clay is essential for the for the identification, classification followed by realistic evaluation of the formation. Presence of silt is noticed in the entire Barail section with positive and negative co-variances on SP-GR and resistivity-GR curves respectively. Presence of silt always increases the resistivity as compared to the clean water bearing section of the reservoirs. Predominant presence of non-conducting silt does not allow the use of conventional shaly-sand or conducting silt model. Silt-sand model using Archie's equation gives the realistic values of porosity and water saturations.

To compensate the bi-directional behavior of SP and Gamma ray due to grain size variations, new term 'Pseudo silt' was introduced as an additional matrix component of sand matrix in addition to silt and clay. Presence of pseudo silt is also noticed throughout the Tipam and Barail sections with negative covariance on SP-GR curves. Positive covariance of resistivity and gamma ray curves is mainly associated with surface conductance phenomenon coupled with smaller grain size and very low salinity of formation water and gives false impression of fresh water shaly sands. A water saturation equation with variable 'm', namely "Assam Equation" is to be used to take care of surface conductance effects associated with very fine grained low resistive pseudo silt facie. Sometimes positive correlation of resistivity and gamma ray curves, noticed in hydrocarbon bearing zones, may be due to the higher values of irreducible water saturations coupled with smaller grain sizes.

In this paper, a complete procedure for the selection of different interpretation models through visual co-variances of log motifs is illustrated with actual field examples of seven types of reservoirs from Tipams and Barails. Lithofacies inversion of open hole logs performed with this approach with appropriate saturation model have resulted in a realistic evaluation of all types of reservoirs varying in the range from Archie, non-Archie shaly to severely non-Archie low resistivity reservoirs. This approach takes care of all the concepts viz. anomalous SP, salt water concept, surface conductance effects and anomalous reduction of Petrophysical parameters on core measurements, in addition to clay effects put forward by different log analysts in the past.

Introduction

Fresh water Tertiary reservoirs of oil fields of Upper Assam Basin located north eastern part of India are generally very complex and heterogeneous, ranging from clean sands-Archie reservoirs to very complex low resistive- severely non Archie reservoirs, encompassing entire range of classification of reservoir rocks (Worthington, 2010) with two to four fold reduction on formation resistivity factor and needs a wide spectrum of interpretation models for the realistic evaluations of logs.

Micas, feldspars and heavy minerals are generally associated with very fine grained sand reservoirs and present a false picture of shaly sands at first glance due to its similar response on most of the logging tools viz. gamma ray, neutron-density separation. However, neutron, sonic, caliper and SP are affected differently in the presence of the above minerals. Clay increases neutron and sonic responses and SP shift towards shale base line, whereas other minerals leaves sonic, SP and sometimes neutron responses unchanged, which clearly exhibit it as sand reservoirs on those logs. Unidirectional behavior from sand to clay is not seen on SP, sonic transit time and sometimes neutron as well as on core measurements. Average matrix sonic transit time of the mica and feldspar are close to sand and it is least affected as long as porosity and clay fractions remains more or less same. Parallelism of three porosity curves clearly indicates that average lithology and porosity is not changing which can be correlated to produce a hundred percent deviation on gamma and resistivity logs. There are very large variations of reservoir facie on log motifs. Clean sand reservoir with 6-7 LPU negative separation on neutron-density in a well becomes 6-7 LPU positive in the next well. These variations on log motifs are mainly associated with grain size variations with presence of mica and/or feldspars and give the false impression of 30-40% shale/clay on conventional shale volume estimations. To compensate the bi-directional behavior of SP and Gamma ray due to grain size variations, new term "*Pseudo silt*" was introduced as an additional matrix component of sand matrix in addition to silt and clay. Volume of pseudo silt is estimated as difference of sand volumes seen by Gamma and SP logs (Yadav, 2015).

Identification and quantification of surface conductance phenomenon associated with grain size variations in silt/pseudo silt type of facie is very crucial as it gives the false impression of excess conductance like clay in fresh water shaly sands. Silt /pseudo silt or very fine grained sand component may or may not be exhibiting conduction of electrical currents depending on the absolute value of formation water resistivity as surface conductance phenomenon is associated only with fresh water. Pre-knowledge about the conductivity behavior of the matrix, particularly silt and pseudo silt, in addition to clay is essential for the realistic evaluation of the formation. Silt and clay may have common behavior on most of the log motifs but silt component may or may not be exhibiting conduction of electrical currents depending on the nature of its distribution and fluid content particularly formation water salinity which exhibits very large variation from ~1.0 kppm in Tipam Sand-1 to ~10 kppm in Sylhet/Kopili formations. In this paper, a complete procedure for the identification, classifications and selection of different interpretation models through visual co-variances of log motifs is illustrated with actual field examples from tertiary reservoirs of Upper Assam Basin.

Basic concept of visual co-variances of log motifs

Correlation is a measure of relationship between points in a plane. A linear correlation measures the change in either variable corresponding to unit change in the other variable when the units are made comparable. In case of covariance, relationship between two variables is seen without any normalization of individual units without plotting in variable plane. Two logs are said to have positive or negative covariance if both are increasing or decreasing simultaneously with respect to each other. Log motifs with independent behavior are said to have zero correlation or covariance.

Covariance of log motifs is to be considered as variance according to lithological effects and is independent of increase or decrease of its absolute value. To be more specific, SP and GR log motifs are said to be having positive correlation if both are showing unidirectional behavior for shale or sand layers defined by base lines on these logs. Opposite behavior is to be defined as negative covariance or correlation. Variation of GR is indicative of shale component of lithology and positive covariance of GR – RT curves indicates decrease of RT values with increase of GR values associated with shale component of lithology. To see the correlation, logs are to be displayed in normalized scale or maximum and minimum values are tied together. Tracking of the curves is indicative of positive correlation and departure of the curves indicates negative correlation.

Identification of different reservoir facie and interpretation models through visual covariance of log motifs

Validity of precise prediction of water saturation depends on the proper selection of resistivity equation which takes care of both lithology and water components in water bearing zone of the reservoir. For example, little variation on porosity and clay, cannot take care of large variations on resistivity for the precise computation of water saturation close to hundred percent in the known aquifers. Correlation of resistivity with other logs mentioned in the paper pertains only to the aquifers, where resistivity is supposed be mainly varying with lithology/ shale/facies with little variance on porosity.

i. Positive correlation SP- GR and zero correlation of GR- RT: Clean Sand model

Positive correlation of SP–GR without variation indicates clean sand model. Clean sandstone reservoirs are indicated with constant deflection on SP and GR overlapping each other. Variations of true formation resistivity (Rt) are noticed with water fraction of porosity in accordance with Archie's equation. All the reservoirs of Upper Assam oil fields exhibit fining or coarsening upward behavior with classical bell or funnel shapes on SP-GR. Accordingly, Archie's reservoirs makes the top or bottom part of shaly sand reservoirs. Reservoirs with log motifs quite close to clean sands are sometimes noticed in a portion of reservoir in the crestal parts of the Fields. Log motifs and processed logs of Archie reservoir from lower Tipams are presented in Fig-1.

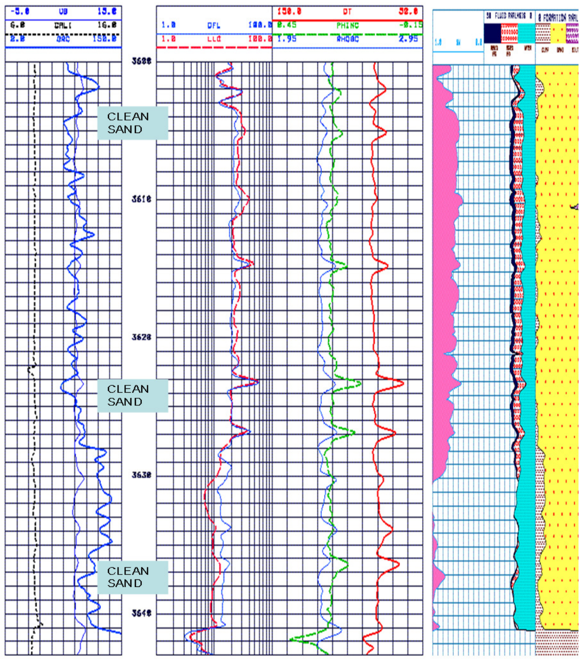

Fig-1.Covariance of log motifs and processing results in clean sand reservoirs of Lower Tipams

ii. Positive correlation of SP-GR and negative correlation of GR - RT: Silt–Sand model

Positive correlation of SP–GR indicates conventional silt sand model. Shale beds are generally represented distinctly and predominantly by silt component showing unidirectional behavior on SP, GR and opposite or negative correlation on GR-RT. SP and GR curves track each other respectively in cleanest portion of aquifer and shale i.e. sand and shale base lines. Clay component is characterized with lower resistivity, lower density and higher transit times as compared to adjacent sand beds. It is the sonic transit time, which clearly distinguishes between clay and silt (Fig-2).

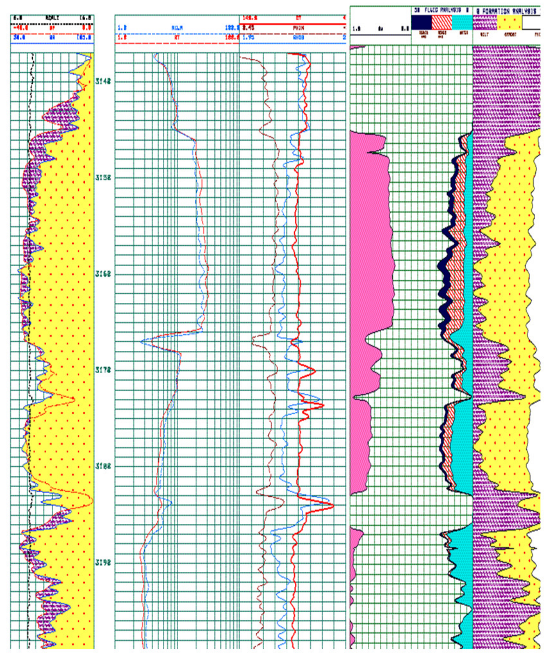

Fig-2. Covariance of log motifs and processing results in silt – sand reservoirs of Barails.

Predominant presence of silt in the shale beds on the top of the reservoir makes sonic transit time lower than the underlying sand bed. Presence of silt is marked with increase resistivity. Constant values of SP – GR indicates nonradioactive very fine sand or silt giving false impression of conventional shale on density and resistivity logs. Grain size variations are not reflected on GR due to predominance of quartz in silt. Sonic transit time and neutron indicate more or less porosity similar to adjacent clean sand beds. Such types of reservoirs are to be processed with silt-sand model using Archie's equation. In hydrocarbon bearing zones, decrease of resistivity is coupled with higher irreducible water saturations associated with smaller grain sizes.

iii. Negative correlation of SP-GR and negative correlation of GR-RT: non conducting pseudo silt – sand model

This is the most common reservoir facie present in Barail formations of Upper Assam oil fields. Good SP and mud cake developments are generally noticed with this facie.

To compensate the bi-directional behavior of SP and Gamma ray i.e. negative covariance, a new concept of "Pseudo silt "is introduced as an additional component of sand matrix. It represents fine to very fine sand as seen on core samples. Volume of pseudo silt is estimated as difference of sand volumes seen by Gamma and SP logs. It will take care of grain size variation coupled with mica and feldspar components of the sand matrix. Micaceous fraction perhaps behaves like clay, concentrated in suspension load in spite of high density due to its flaky nature (Serra, 1985)

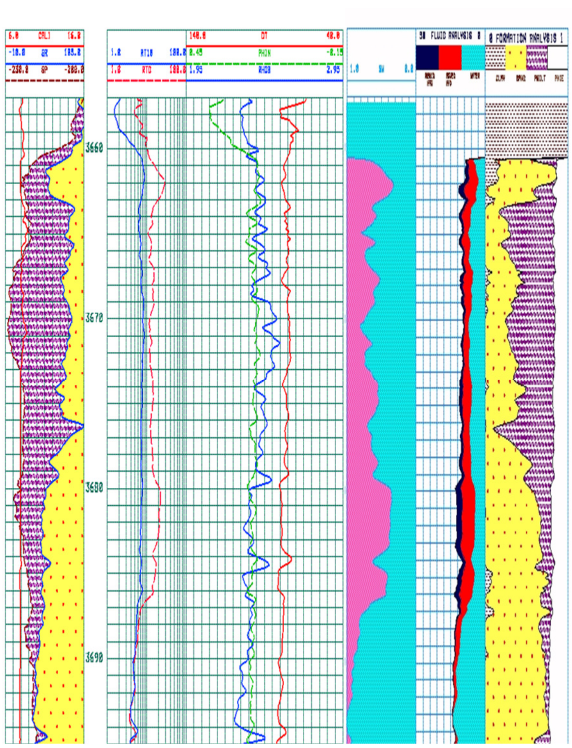

Fig-3. Processing results in non-conducting pseudo silt reservoirs in Barail Coal Shale

Effect of silt/clay component of matrix gets cancelled, if SP and Gamma ray curves are displayed in same span by making these curves to track each other respectively in the cleanest portion of aquifer and shale i.e. sand and shale base lines. This fact is clearly illustrated by field examples from Barail Main Sands Fig-2. Presence of silt makes SP and Gamma ray logs tracking each other. Conventional silt is clearly indicated by increase of density, resistivity, gamma and SP close to shale base line.

Presence of pseudo silt characterized by high GR, PHIN ($<PHIN_{Clay}$) and RHOB does not show any positive correlation with resistivity in this case. So, Archie's equation has to be selected for computation of water saturation. In hydrocarbon bearing zones, decrease of resistivity is coupled with higher irreducible water saturations associated with smaller grain sizes. Log motifs of field examples from Barail Coale Shale reservoirs are presented in Fig-3 along with respective processed results.

iv. Negative correlation of SP-GR and positive correlation of GR-RT: conducting pseudo silt – sand model

This type of facies are characterized by fining upward sequence or cycle of fining upward sequences, coupled with decrease of resistivity, increase of gamma and shale like separation on neutron and density log measurements. Close scrutiny of the log characters and available core measurements related with low resistive complex reservoir facies clearly indicates its presence everywhere and in every level from Tipam Sand -1 to 5, with varying thicknesses in Upper Assam Oil fields.

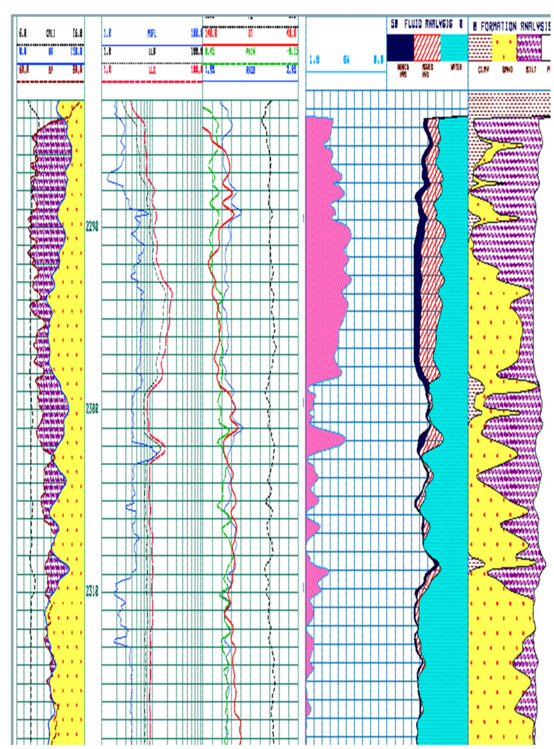

Fig-4. Co-variances of log motifs and processing results with conducting pseudo silt in Upper Tipams

At a first glance, fall of deep resistivity log at the top of the zone seems to be related with lithology i.e. presence of clay indicated by high gamma and positive separation on neutron and density logs.

However this fact is not seen on SP, Sonic and CMR logs. Co-variances of log motifs clearly reveals that porosity and clay components are almost constant with little variation even in known water filled aquifers where two to four fold resistivity variations are noticed. When clay volume, porosity and formation water resistivity are not varying, such a large variation of resistivity or variation of formation factor can only be compensated through variable "m", i.e. cementation exponent in Archie's equation for the precise computation of water saturation close to a value of hundred percent.

To quantify the surface conductance related with low resistive facie, a unified relationship between "m" and pseudo silt volume has been evolved through linear regression analysis, which have resulted in a unified equation, called "Assam Equation". It is basically Indonesian equation with variable "m" and "n", which allows varying these parameters from clean-sand to pseudo silt, as a function of pseudo silt volume. Field examples from upper Tipam sand -2 presented in Fig-4.

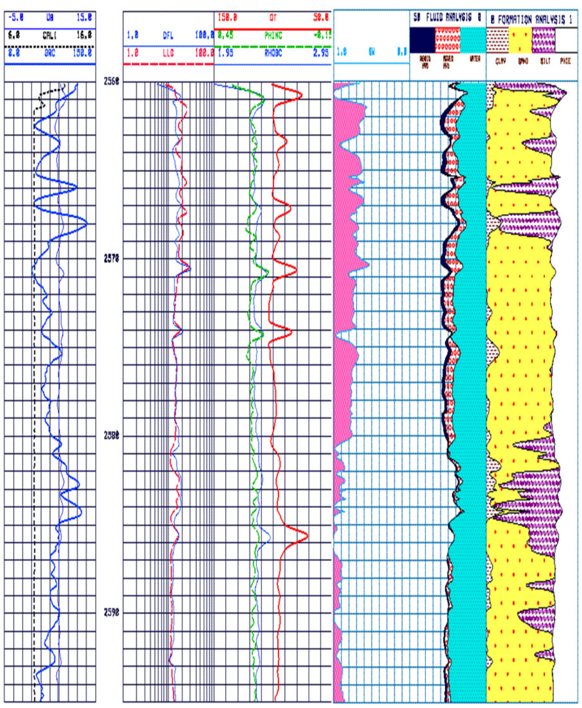

Fig-5. Covariance of log motifs and processing results in feldspathic silt -sand reservores in Upper Tipams

v. No correlation of SP-GR and no correlation of GR-RT- silt (feldspathic) -sand model

Presence of radioactive potassium feldspars in very fine grained sand stone reservoir increase the GR values with little decrease on density and neutron values and leaves SP unchanged as compared to clean sand reservoirs. Log motifs of upper Tipams exhibiting such character are presented in Fig-5. Zero correlation of GR-RT indicates either bigger grain size or higher formation water salinity than optimum values required to produce surface conductance phenomenon. Such reservoirs can easily be processed with silt-sand model, where silt properties are close to feldspars.

vi. Hydrocarbon accumulation with facie variations

Sometimes, Tipam Sand-4 and 5 reservoirs of are generally known as low resistive reservoirs but these do not make the case of classical low resistive interpretation approach for log evaluation. These reservoirs are quite clean and oil accumulations are confined to several sub-layers as indicated in Fig-6. Negative covariance/ anti-correlation of resistivity

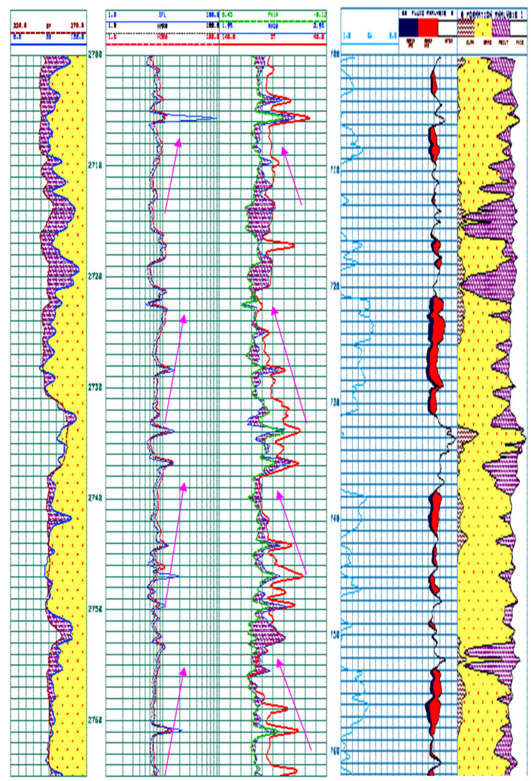

Fig-6. Covariance of log motifs and processing results in low resistive reservoirs with facie variation in Tipam Sand-4 and 5.

and porosity logs (pink arrows) clearly indicate classical increase of oil saturations through Archie's law. Generally oil accumulations are associated with increase of porosity or better facies without increase on resistivity due to constant value of water volume (Phi*Sw). Increase of resistivity is not related with hydrocarbon accumulation but it is related to decrease of water filled porosity. A value of 50% water saturation may be related to either fourfold increase of resistivity or two fold increase of porosity. Classical behavior of increase of sonic transit time with constant/increase of resistivity, generally associated with hydrocarbon bearing layers in the field is generally noticed as per Archie's equation and does not make the case of low resistivity. Silt layers with 100 % Swi values (Capillary water) are acting as barriers as indicated on CMR log recorded.

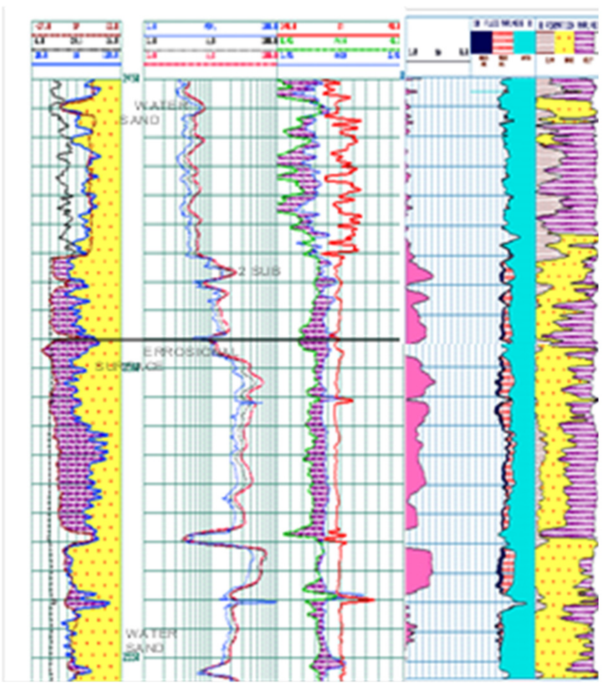

Fig-7. Covariance of log motifs and processing results in Low resistive reservoirs with change of salinity in main Sand and TS-2 Sub

vii. Change of formation water salinity

All the TS-2 Subs of main of main sand are known to be oil bearing and generally referred as low resistive reservoirs (?). Covariances of log motifs clearly indicate that it does not make the case of low resistive facie. An example of low resistive reservoirs, namely TS-2 Sub of a Well indicated in Fig-7, actually make the case of change of formation water salinity.

All the logs indicate that lithologically and porosity wise, this zone is similar to the cleaner portion of the reservoir in the interval 2503-2533 m, where resistivity is of the order of 60 ohm-m. Three time decrease of resistivity of the zone i.e. 20 ohm-m may only be attributed to the change of Ro from 24 ohm-m to 8 ohm-m, where other parameters are same. This can be easily explained with higher water salinity associated with low energy depositional environment of Girujan Clays as compared to the low water salinity with higher energy depositional environment of Tipam Sand -2.

Discussions and Conclusions

Silicilastic sandstone reservoirs of Upper Assam oil fields are very complex and contain large and varying amounts of micas, feldspars and also, very often, heavy minerals in addition to quartz and clays.
On core measurements these facies are generally described as moderately to well sorted, medium to fine to very fine-grained sands. A small amount of clay volume rarely exceeding 5 %, can only produce variances on logs, which is within the measurement uncertainty limits of tools. It is very difficult to precisely assess the clay volume fractions from logs. Possibility of predominant presence of shale/clay is clearly ruled out on electrical image and nuclear magnetic resonance logs. It is basically very fine grained micaceous / feldspathic sand exhibiting clay like behavior on some logs.

For the realistic evaluation of such types of reservoirs, a multi-mineral model approach has been suggested in past WEC, 1974, 1983 and by Suau and Spurlin, 1984, to take care of predominant presence of these minerals. Pre-knowledge of volume fractions of different rock constituents from core measurements becomes very crucial and is not always available to log analyst for the precise calibration. Moreover, presence of mica and feldspars did not allow actual compensation of excess conductivity using shaly sand or conducting silt models. Use of conducting mineral in addition to clay, through multi-mineral model has not been efficacious to deal with the situation as these were minor components. Meaningful validation of S_w equation can be ensured only in the aquifers having similar facie or lithological complexity. In most of the underlying water bearing zone of the reservoirs do not make the proper reference for the computation of water filled resistivity of the rocks in hydrocarbon zones.

To overcome these limitations, lithofacie inversion of open hole logs through textural model provides a simple and accurate method for the evaluation based on grain size evolution and subsequent prediction of producibility of reservoirs and do not require core measurements for validation of interpretation results. It is an special case of dual mineral model where one additional component namely silt or 'pseudo silt' is defined through cross plots to take care of predominant mineral as well as grain size in addition to clean sand and clay. Realistic reservoir evaluation can only be performed through silt or pseudo silt–sand model in accordance with co-variances of SP-GR curves. Positive or negative co-variances indicate the presence of silt or pseudo silt respectively.

Sometimes positive correlation of resistivity and gamma ray curves, noticed in hydrocarbon bearing zones, may be due to the higher value of irreducible water saturations coupled with smaller grain size. This has to be confirmed by processing and comparing results by using both conducting as well as non-conducting pseudo silt equations. Decrease of water saturation against pseudo silts as compared to the cleaner portions of the reservoir is reverse to the basic concept and indicates the over correction of resistivity and underestimation of water saturation values than the real one. Decrease of resistivity is due to real increase of irreducible water saturations with decrease of grain size. Identification of different interpretation models with water saturation equations through visual co-variances of log motifs are summarized in Table-I. Clean sand, pseudo silt reservoirs and non-reservoir silts are clearly distinguished on co-variances of log motifs.

Table-I. Summary of Covariance of log motifs and Interpretation models for reservoirs of Upper Assam

Correlation of SP-GR	*Correlation of GR- RT*	*Interpretation model and water saturation equation*
Positive	*Zero*	*Clean sand, Archie's equation*
Positive	*Positive*	*Shaly-sand Model, Indonesian equation*
Positive	*Negative*	*Silt-sand model, Archie's equation*
Negative	*Negative*	*Pseudo silt-sand Model, Archie's equation*
Negative	*Positive*	*Pseudo silt -sand Model, Assam equation*
Zero	*Zero*	*Multi-mineral, Archie's equation*

It is worth mentioning that covariance of log motif represents real picture of the reservoir which may be obliterated by processing artifacts or wrong selection of model or model parameters. Visualization of interpretation model on covariance of logs for prediction of major constituents of the rock is very crucial for inversion of logs. It is not only the errors on hydrocarbon reserves but geological models are seriously affected by wrong picture presented through conventional approach. For example, reporting oil shale contact in Tertiary reservoirs of a well on shaly sand model instead of oil water contact on processed results with Assam equation will seriously affect the geological model of the producing reservoir. Selection of interpretation model, predominant facie and model parameters selection through covariance technique is very crucial and ensures meaningful formation evaluation with greater degree of confidence/ authenticity.

References

Archie, G. E, 1942, The electrical resistivity log as an aid in determining some reservoir characteristics, SPE-AIME, transactions Vol. 146.

Itenberg, S. S., Koithara, J. and Hashmy, K. H., 1969, The Status of Well Log Interpretation in India, SPWLA, Tenth Annual Logging Symposium, May 25-28.

Jain, P. K., 1990, "Anomalous low resistivity Tipam Sands of Assam, India, and their observed petrophysical aspects," Proceedings of the 8th SPE Offshore South East Asia Conference, 393-400

Koithara, J., Bisht, J. S. and Nohwar, U. V. S., 1973, Review of results of some petrophysical studies on cores from Assam oil fields, India, SPWLA, Fourteenth Annual Logging Symposium, May 6-9.

Sarma, V.V.J. and Rao, V.B., 1963, Variation of electrical resistivity of river sands, calcite and quartz powders with water contact, Geophysics.

Schlumberger, Well Evaluation Conference (WEC), 1974, India, 1983

Suau, J. and Spurlin, J., 1984, Interpretation of Micaceous sandstones in the North Sea, SPWLA, Twenty Third Annual Logging Symposium, July, 6-9.

Worthington, P. F., 2010, Quality assured Evaluation of fresh water bearing hydrocarbon reservoirs, SPE-133898, SPE Asia Pacific Oil & Gas Conference and Exhibition, Brisbane, Australia, 18–20 October

Yadav, Lalaji, 2015, Electrical Characterization of Low Resistivity Fresh Water Fluvial Reservoirs Using Variable Cementation Exponent 'm', 3 rd CEWELL symposium, ONGC, Ahemdabad, India